A RIVER IN TRANSITION:
GEOMORPHIC AND BED SEDIMENT RESPONSE TO COCHITI DAM ON THE MIDDLE RIO GRANDE, BERNALILLO TO ALBUQUERQUE, NEW MEXICO

BY

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**B.S. , EARTH AND PLANETARY SCIENCES,
UNIVERSITY OF NEW MEXICO, 2000**

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**Master of Science
Earth and Planetary Sciences**

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DEDICATION

I dedicate my thesis to my parents Sam and Jan Ortiz and to my advisor Dr. Grant Meyer.

My Mom and Dad provided infinite amounts of love and encouragement which helped pull me through times when I thought this project would never get finished. They put up with numerous moments of frustration and despair. Without their undying love, patience and support I would not be the man I am today.

Grant has had undying faith and infinite patience with me during this study. When I started this project my knowledge of Geomorphology was very limited. Grant took a chance and allowed me to study under his guidance. He has taught me many things over the last few years; from the basic fundamentals of fluvial geomorphology and the importance of understanding surficial processes and their effects on local and regional geomorphic settings, to the perfection of a draw stroke and a fly cast. Not only has he been a great mentor, he has been a great friend and colleague. He has always treated me with respect, listened to my interpretations and ideas, and gently guided me in the right direction. It has been a pleasure and an honor to work under the tutelage of such a well respected process geomorphologist. Grant, thank you for all that you have done. I am full of gratitude and forever in your debt.

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There are many people I'd like to thank who have helped in someway with the completion of this project. First and foremost I'd like to thank my family, Sam, Jan, Rob and Julie. Thanks for the love and support. I'd also like to thank my Graduate Committee, Dr. Grant Meyer (chair), Dr. Les McFadden and Dr. Gary Smith. Without their guidance, support and constructive criticism my thesis would still not be finished. I'd also like to thank Tamara Massong and the United States Bureau of Reclamation which provided the necessary funding and a portion of the data used for this project. The Department of Earth and Planetary Sciences has also provided supplemental funding for this project. The Department has been a wonderful home for me during my graduate and undergraduate education and I will miss walking its hallways.

I'd also like to thank the numerous support people who helped in the field and back in the lab. My field assistants were wonderful. They included Dr. Grant Meyer, Chris Purcell, Jeff Parker, James Ashby, Chris Hepler, Lyman Persico, Dan Breecker, Paul Burger and my dog Sugar. Shannon Duran helped in the lab running numerous dry sieve analyses. Jen Pierce was the ultimate QSL companion. It was a pleasure having her as my unofficial officemate. She was always there with a cheerful smile, supportive hug, or congratulatory high-five. Thanks Jen you are the best!

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Last but not least I would like to thank Cindy Jaramillo of the Department of Earth and Planetary Sciences. She has always gone above and beyond the call of duty helping me and all the other graduate students. Because of her I never missed an OGS deadline. Thanks Cindy! You're the greatest!

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ABSTRACT

75 years of channel and floodplain modification has greatly altered the middle Rio Grande fluvial system. Dams, levees, and various generations of bank stabilization projects have confined the river to a narrow valley and greatly altered discharge and sediment supply regimes as population centers have grown along its path. The Rio Grande drains more that 273,530 km^2 of the southwestern United States and northern Mexico, with 37,555 km^2 of the basin directly contributing to the flow of the river through the study reach, near Albuquerque, New Mexico. This study specifically investigates the effects Cochiti Dam has had on the Rio Grande over the past 30 years.

Prior to Cochiti Dam, bed sediment was comprised of sand and/or gravel depending on discharge. It's estimated that ~80% of sediment inflow to the middle Rio Grande is trapped by three major dams, with Cochiti alone receiving ~2.2x10^6 m^3 of sediment a year. A 31-year pre-dam record and a 23-year post-dam record of discharge data show that peak discharges below Cochiti have remained similar, the primary difference being the lack of large flood flows greater than 283 m^3/s. Directly after closure of Cochiti Dam in 1973, the study reach experienced a coarsening of bed sediments from fine sand to medium sand. This coarsening occurred prior to the development of a transition zone, between coarse and fine-grained sediments, which has migrated downstream into the study area. Through the use of geomorphic and geologic techniques this study characterizes the effects Cochiti dam has had on a 25.5 km study reach of the middle Rio Grande. It specifically addresses Cochiti dam induced downstream changes in channel morphology and the development of a bed-load sediment grain size transition zone.

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INTRODUCTION

To better understand the long-term effects of dam operations and other anthropogenic and natural influences on the middle Rio Grande, the Bureau of Reclamation has provided funding for a geomorphic study of a 25.5 km reach from the US 550 bridge in Bernalillo to the Montano Street bridge in north Albuquerque (Figure 1). Since the construction of Cochiti Dam, the middle Rio Grande downstream from the dam site has undergone significant morphological changes (Lagasse, 1980). These changes include stream channel degradation, narrowing and straightening of the channel, and a coarsening of bed sediment within the active wetted perimeter of the channel. The active channel is defined as the area between the abandoned floodplain surfaces that is unvegetated and has a significant probability of inundation during the year. Although some of these changes began to occur prior to dam construction as a result of specific reclamation efforts, these channel changes became exacerbated after dam construction was completed (Lagasse, 1980).

This study is part of a larger regional study of the Rio Grande currently being conducted by the Bureau of Reclamation in conjunction with the University of New Mexico in Albuquerque and Colorado State University in Fort Collins. This larger study is focusing on the large-scale channel adjustments occurring along the entire length of the middle Rio Grande south of Cochiti Dam. Richard (2001) was one of the first contributors to this project. Her Ph.D. dissertation focused on modeling the channel changes of the Rio Grande directly downstream of Cochiti Dam. Richard (2001) concluded that based on the modeling of historic channel adjustments the Rio Grande, in response to Cochiti Dam, is headed towards a more stable channel configuration.

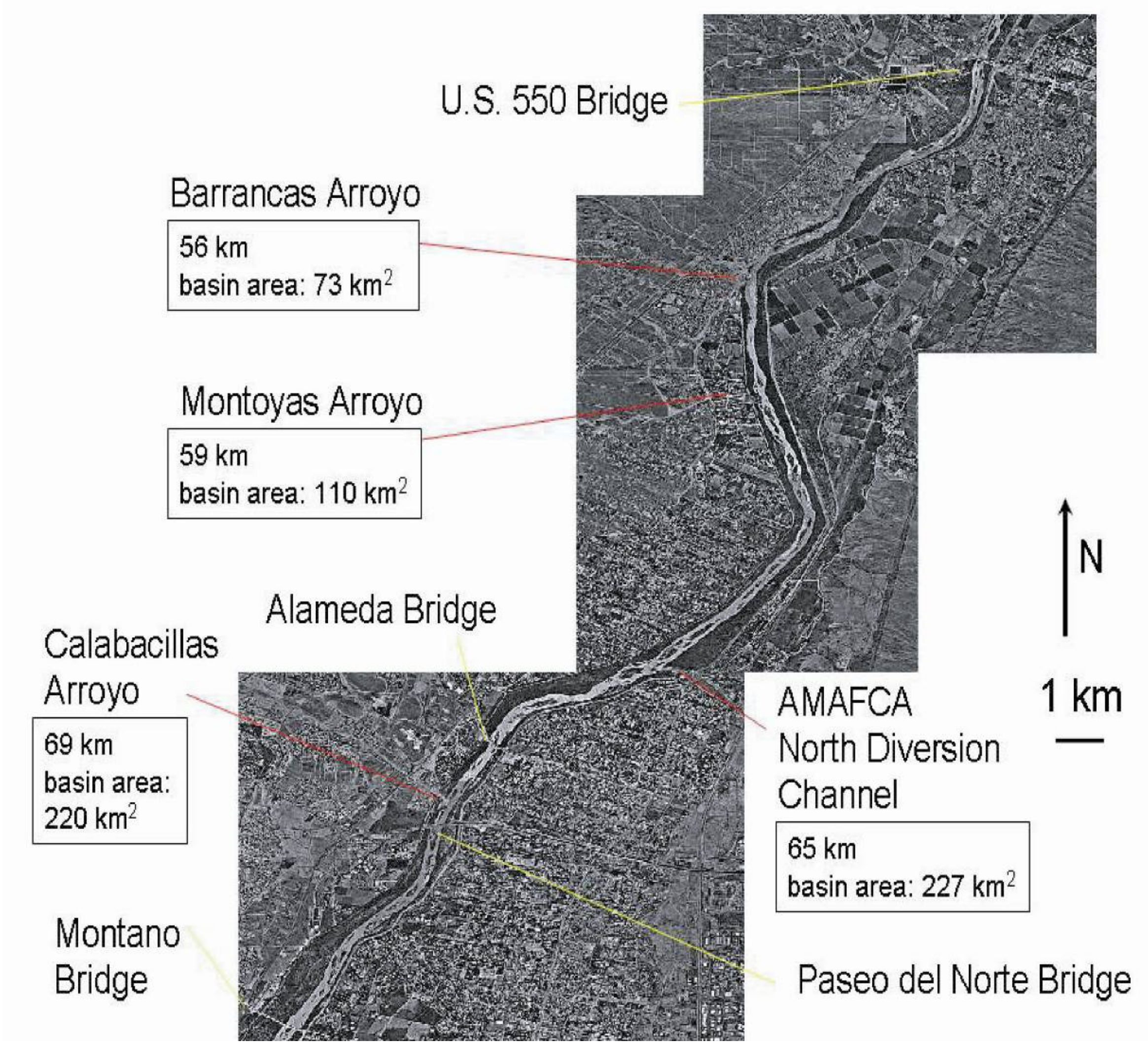


Figure 1 Mosaic of USGS air photos of the study reach. The reach extends from U.S. 550 Bridge in Bernalillo in the north to Montano Bridge in the south. Length of reach is 25.5 river kilometers. Resolution is 16 meters.

Prior to dam construction, the middle Rio Grande channel contained many non-vegetated bars and islands, with bed sediment within the study reach composed primarily of fine and medium sands and lesser patches of gravel. It has been estimated that ~80% of sediment inflow to the middle Rio Grande is trapped by Cochiti, Jemez, and Galisteo dams, with Cochiti alone receiving ~2.2 x 10^6 m^3 of sediment a year (Lagasse, 1994, Baird and Sanchez, 1997). A 31-year pre-dam record and a 23-year post-dam record of discharge data at the Central Bridge gauge in Albuquerque show that peak discharges below Cochiti have not changed markedly, the primary difference being the lack of large flood flows greater than 283 m^3/s (10,000 ft^3/s) (Figure 2).

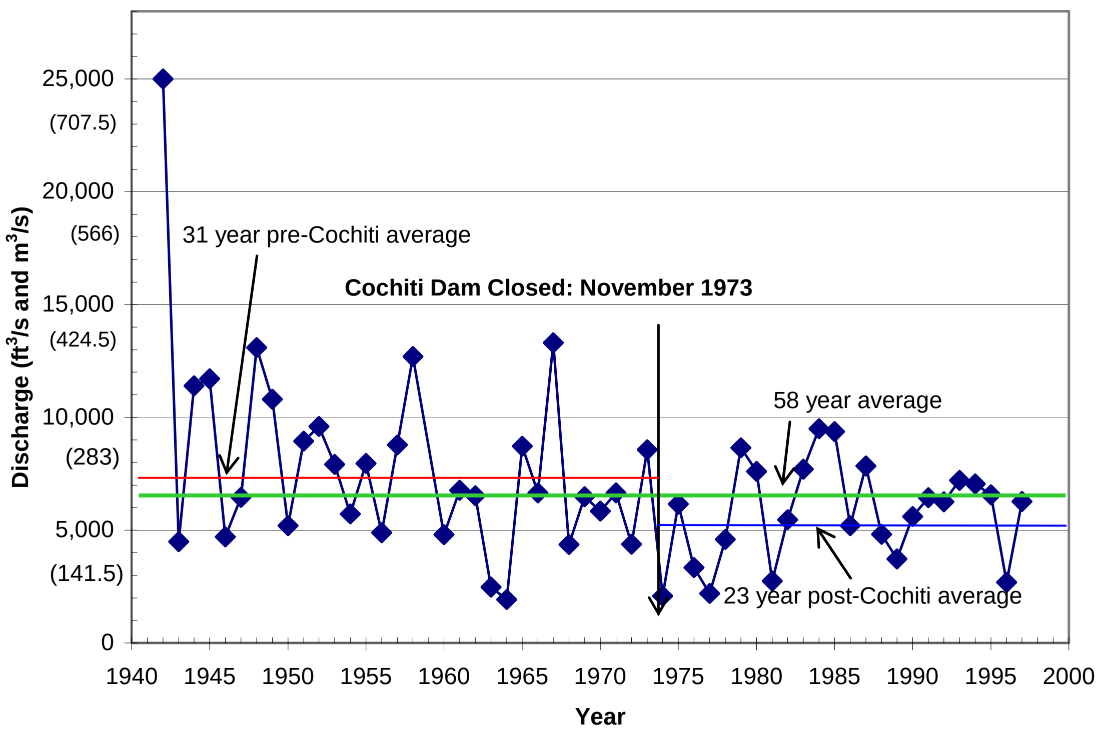


Figure 2 Plot of the annual peak discharges for the 58 year USGS gage record of the Rio Grande at Albuquerque (gage ID: 08330000). Lines indicate the average discharge for the entire record, as well as pre and post-Cochiti average discharges.

The highest discharges recorded at the Albuquerque gauge since the construction of Cochiti Dam occurred in 1984 (9,500 ft^3/s) and 1985 (9,370 ft^3/s). According to Harvey (2003), flows of this magnitude had a pre-dam recurrence interval of between 2 and 5 years (Figure 3). A longer pre-dam record indicates that peak discharges in the 31-

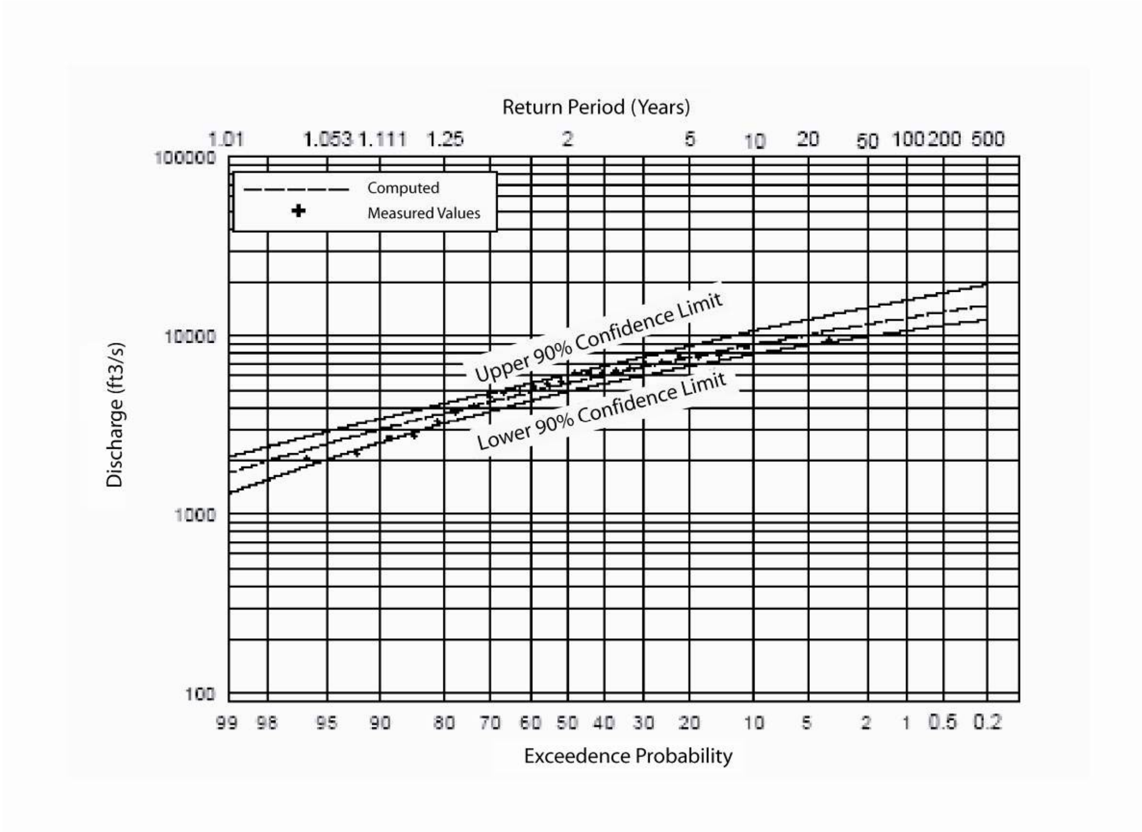


Figure 3 Post-Cochiti flood-frequency curve for the Rio Grande at the Albuquerque gage (Fig. 3.13 from Harvey, 2003).

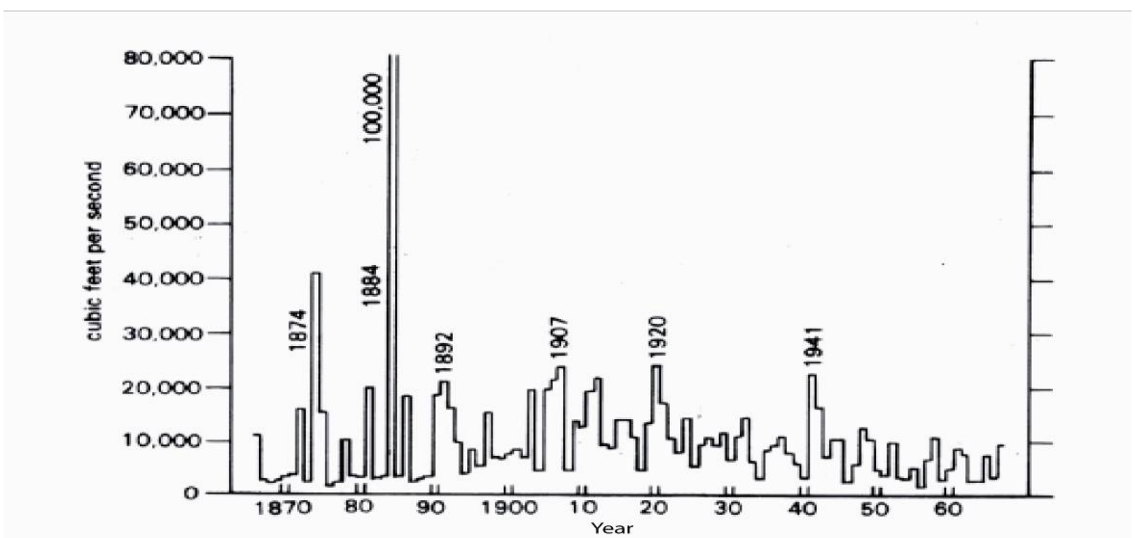


Figure 4 Pre-dam peak discharge recorded for the Rio Grande from the middle 1860's to the late 1960's. Discharges are measured in cubic feet per second (10,000 ft^3/s = 283 m^3/s) (from Kelley, 1982).

year pre-dam period are relatively low compared to earlier discharge records dating back to the late 1860s (Kelley, 1982), however, the original source and reliability of the Kelley, 1982 data are unclear (Figure 4).

The channel bed began to degrade and become coarser and locally armored below Cochiti Dam shortly after its closure (Lagasse, 1980; Williams and Wolman, 1984). The armoring of the channel directly below the dam was facilitated by the presence of gravel below a thin layer of sand (Culbertson and Dawdy, 1964). The presence of large amounts of gravel within the upper reaches of the middle Rio Grande and scarcity of gravels within the Albuquerque reaches of the middle Rio Grande was also observed and recorded by Rittenhouse (1944), who stated that "in the upper part of the middle Rio Grande channel deposits consist of fine to medium sands overlying a bed pavement of cobbles and pebbles. Downstream the gravel becomes less abundant and below Albuquerque, seldom constitutes more than a few percent of the upper 5 feet of the deposits". Nordin and Beverage (1965) further indicated that the Rio Grande became a sand-dominated channel south of the confluence with the Jemez River, which was a large source of sediment to the Rio Grande prior to being dammed (Figure 5). A transition zone between the coarser bed of pebble and cobble gravels and a fine to medium sand bed similar to pre-dam conditions migrated downstream at a rate of ~5 km/yr between 1973 and 1980, but this rate has slowed over the last 30 years, likely in part because of sediment inputs from major tributaries downstream, including Galisteo Creek, Arroyo Tonque, the Jemez River, and Arroyo de las Barrancas (Lagasse, 1981). It is not known if the current transition zone that has developed is stable or still migrating downstream.

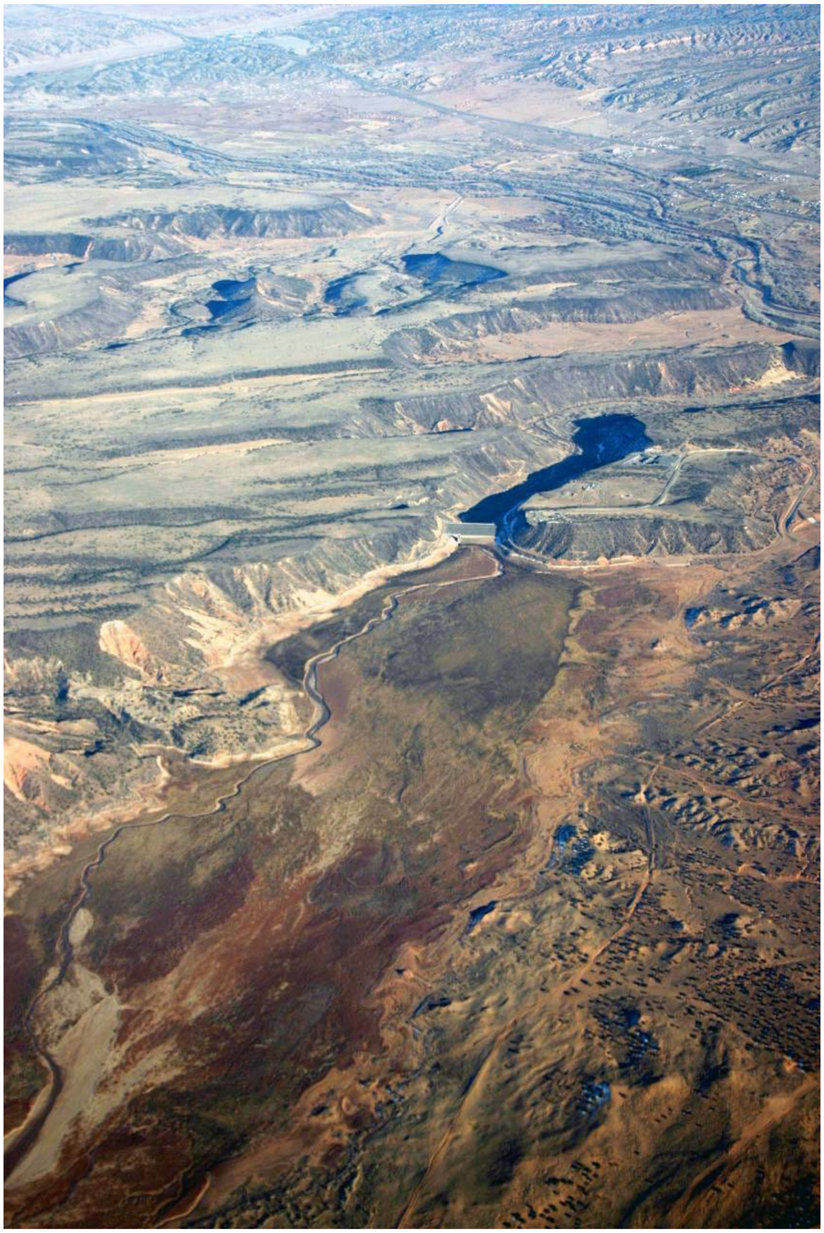


Figure 5 Oblique air photo showing the Jemez River flowing east-northeast to Jemez Canyon Dam and the large accumulation of stored sediment trapped above the dam, visible when the reservoir drained in 2003. Notice the narrow, incised channel of the Jemez River, indicating relatively minor sediment removal from above the dam. Prior to dam construction on the Jemez the majority of the sediment stored above the dam would have entered the mainstem Rio Grande, which flows from left to right at the top of the photo.

The specific purpose of this study is to investigate and document the changes that have occurred within the Bernalillo-Albuquerque study reach after completion of Cochiti dam in 1973. A primary focus of this study is the transition zone between an upstream reach altered by dam effects and a downstream reach that is relatively little affected.

Initial observations show that the transition zone is identified by changes in channel planform morphology and median grain sizes of bed load material. Within the study reach, channel planform changes from a narrower, dominantly single-threaded and locally island-braided planform upstream, to a broader and shallower multi-threaded island- and bar-braided planform downstream. Gravelly bed material is found upstream of the transition zone, whereas a sandy bed characterizes the downstream reach. The bed sediment transition zone is not a discrete boundary; it is characterized by a general decrease in gravel within the channel and a decrease in channel depth downstream.

Previous studies (Nordin and Beverage, 1965; Culbertson and Dawdy, 1964; Rittenhouse, 1944), however, have documented that bed material became finer with distance downstream from Cochiti dam, even before its construction. Therefore, a primary goal of this study is to describe channel morphologic and bed material changes in the study reach following closure of the dam, and to separate downstream changes resulting from dam operations from pre-existing conditions.

Other key elements of this study include changes in vegetated island areas, bank and island sediment descriptions, general reach-wide channel morphologies, analysis of a water surface profile and changes in hydraulic geometry parameters since completion of Cochiti dam. Documenting the change in vegetated island areas along the study reach highlights the changes in sediment storage and channel morphology along the reach; in addition study of the bank and island stratigraphy will characterize what type of sediment is being stored along the study reach. The water surface profile can be used to examine slope changes that may stem from local sediment inputs, as well as any larger-scale slope changes that could affect sediment storage and transport along the length of the study reach.

STUDY QUESTIONS AND HYPOTHESES

The main questions posed in this study focus on the transition zone: (1) What geomorphic and sedimentary features define the transition zone? Specifically, (2) how do bed material grain size distributions change with distance downstream, and (3) how does channel morphology change downstream? (4) What effect do bed sediment, bank sediment and vegetated islands have on channel morphology? (5) What factors affect the location of transition zone, and is the transition zone static, or is it currently moving downstream?

Two hypotheses were proposed for this study. One is that relatively little change in bed material has occurred, and that the difference in bed-sediment texture along the study reach reflects mainly pre-dam downstream fining as distance from primary gravel sources above the Jemez River confluence increases. A second hypothesis is that the gravel bed found in the upstream reach is a lag composed of gravels already present within floodplain sediments before channel incision; alternatively, the gravels may have been transported downstream from incising reaches above. These hypotheses were tested using contemporary and historical bed sediment grain size data, contemporary sand depth measurements, and bank and island stratigraphy.

Classic theory suggests that movement of the transition zone downstream through the reach will continue at a progressively slower rate until the system reaches quasi-equilibrium (Williams and Wolman, 1984). Among major factors affecting transition zone dynamics are discharges from Cochiti dam and local tributaries, as well as any sediment released into the channel associated with these flows. The sediment-starved releases from Cochiti Dam are limited in magnitude and relatively consistent, but tributary water and sediment discharges are much less predictable and dependent primarily on the magnitude and intensity of localized storm events. Several large tributaries in the study reach deliver sediment directly into the floodway of the Rio Grande with only minor engineered structures affecting the flow. Tributary flows have been shown to episodically introduce large amounts of sediments into the river (Leopold, 1946). Therefore, one hypothesis is that sediment inputs from tributaries will slow or halt the downstream progress of the transition zone through the reach. Alternatively, continued clear water releases throughout the year from Cochiti Dam will continue to facilitate movement of the zone downstream. The scope of this project will not offer any definitive tests of these hypotheses, but the knowledge gained may steer future researchers towards a clearer understanding.

REGIONAL SETTING AND HISTORY OF THE RIO GRANDE

The Rio Grande drains more that 273,530 km^2 of the southwestern United States and Mexico, with 37,555 km^2 of the basin directly contributing to the flow of the river through the study reach. The river flows from the San Juan Mountains of southern Colorado to the Gulf of Mexico more than 3000 km away (Collier et al., 1996) (Figure 6). Through New Mexico, the Rio Grande flows through a series of continental rift grabens partly filled with Cenozoic axial stream and piedmont deposits of the Santa Fe Group (Bachman and Mehnert, 1978; Lambert, 1968; Dethier, 1999), and Cenozoic and modern fluvial sediments (Connell, 1998). The Middle Rio Grande valley begins at the southern end of White Rock Canyon, southwest of Santa Fe, and extends south for about 230 km to the San Marcial constriction (Lagasse, 1980; Baird and Sanchez, 1997).

Along the middle Rio Grande water withdrawals are primarily for irrigation, although the city of Albuquerque is currently building a semi-permanent diversion dam within the study reach in order to divert the city's share of the San Juan-Chama River Project water for non-agricultural uses. Without the use of Rio Grande water the agricultural infrastructure of the middle Rio Grande corridor would effectively collapse. Although the Rio Grande was influenced by human activities prior to Spanish colonization, the most significant changes have occurred within the last 78 years. Around 1925, various state and federal agencies began to constrain and channelize the river through the use of various methods. The first of these methods were the construction of diversion dams and flood control levees placed parallel to the river. The diversion dams were built in order to facilitate the transfer of river water into the intricate

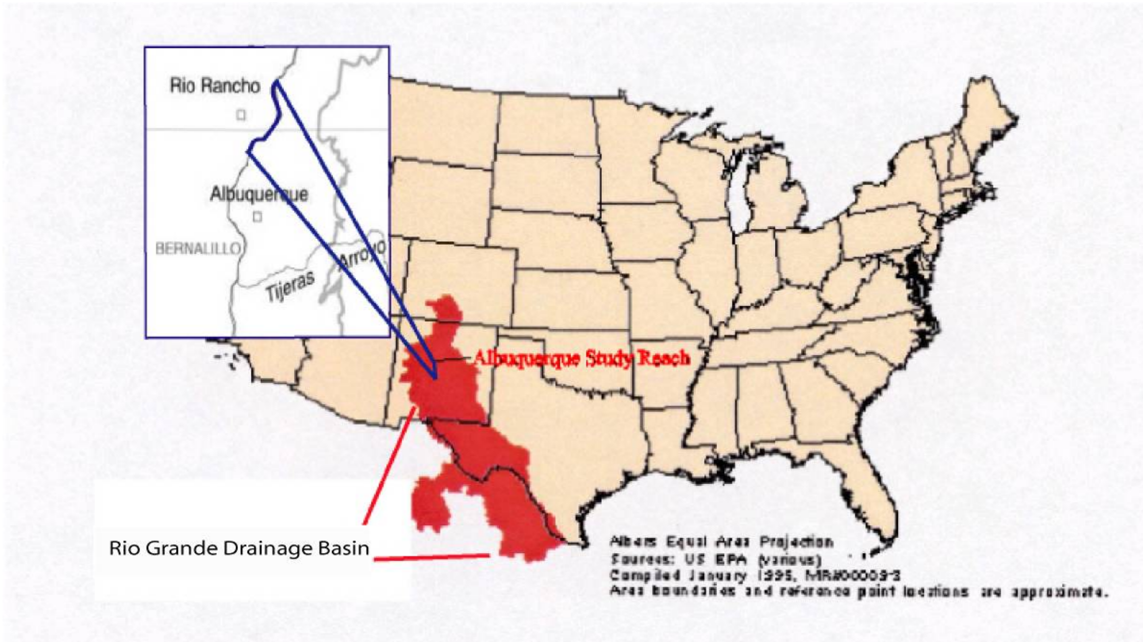


Figure 6 The extent of the Rio Grande drainage basin (reed shading) in the southwestern United States and northern Mexico. Insets highlight the location of the study reach within New Mexico and outline the location of the study reach within the Albuquerque area. Images from the U.S. Environmental Protection Agency (www.epa.gov) and the United States Geological Survey (www.usgs.gov).

system of irrigation canals, ditches and acequias, and to control the length of the irrigation season. Unused irrigation water is returned to the Rio Grande through the use of riverside drains, which run parallel to the floodway of the river. The levees, which constrain the channel of the river to a narrow floodway, were originally a system of locally unconnected and poorly engineered mounds built by local landowners to protect their fields (Lagasse, 1994). With the formation of the Middle Rio Grande Conservancy District, the multiple levee segments were combined and engineered with the remaining piles of debris left over from construction of the riverside drains to protect the majority of the middle valley from large-scale floods (Graf, 1994). Today the Middle Rio Grande Conservancy District controls these levees and diversion dams (Lagasse, 1994).

Dams with uses ranging from flood and sediment control to water storage have been constructed within the middle Rio Grande valley since 1935 when the Middle Rio Grande Conservancy District built El Vado Dam on the Rio Chama (Harvey, 2003). Between 1953 and 1973, the Corps of Engineers constructed one main stem dam at Cochiti and 3 tributary dams: Abiquiu on the Chama River (~ 80 km above Cochiti), Galisteo on Galisteo Creek (12.8 km below Cochiti), and Jemez Canyon on the Jemez River (35.4 km below Cochiti). These dams were originally built to work in conjunction with the levees to provide flood control to the Middle Rio Grande Valley. The three tributary dams are still used as flood control features, but the mandate for Cochiti dam was changed in order for a permanent pool of water to be stored behind the dam. This pool is used for recreational purposes. In addition to the work performed by the Middle Rio Grande Conservancy District and the Corps of Engineers, the Bureau of Reclamation installed Kellner Jetty Jacks extensively along the study reach (Figure 7). These permeable steel structures were used to trap sediment and stabilize the banks of the river with the help of natural vegetation (Lagasse, 1981). Even though jetty jacks are permeable steel structures they create enough roughness within the flow of the river that sediment being transported in suspension is forced to drop out of the flow. The jetty jacks are aligned parallel to the river with numerous perpendicular lines crossing into the floodplain. These perpendicular lines run from the banks of the river to the levees. Although these jetty jack fields are not continuous along the length of the study reach, they are found on more than 50% of the floodplain surfaces.

Figure 7. Photo of Kellner Jetty Jacks along the eastern bank of the Rio Grande in the Corrales area. Banks have remained stable since jetty jack installation during the late 1950's and early 1960's.

STUDY REACH

Located directly north of Albuquerque, New Mexico, the study reach extends 25 km from U.S. Highway 550 in Bernalillo, New Mexico south into Albuquerque to the Montano Street Bridge. The study reach has been divided into two sub reaches. The upstream reach extends from the U.S. 550 Bridge to the Arroyo de las Barrancas, and the downstream reach extends from the Arroyo de las Barrancas to the Montano Street Bridge.

The upstream reach is dominated by a single-threaded, locally island-braided planform, whereas downstream the channel is dominated by a multi-threaded, island- and bar-braided planform (Figure 8). During periods of high discharge the high flow channels become activated and the upstream reach transforms into a multi threaded channel planform. The floodplain along the entire study reach is heavily vegetated with cottonwood, tamarisk, and Russian olive trees, and was last flooded significantly in the early 1940s. Surficial features (paleochannels, bars, and natural levees) within the floodplain are often difficult to discern because of the dense vegetation and large-scale anthropogenic disturbances during levee construction, jetty jack emplacement, bosque fires and rehabilitation work. Currently, bed sediment along the length of the reach varies between cobbles and medium sand, with gravel dominant in the upstream study reach and medium to coarse sands dominant in the downstream study reach.

Figure 8. Oblique air photo, looking North-East, of the U.S. 550 Bridge crossing the Rio Grande at Bernalillo, New Mexico. The narrow, deep, mostly single-threaded low-flow channel planform which dominates the upstream end of the study reach is clearly visible within this photo.

Tributary drainages

Four major tributaries are located within the study reach. Three of these tributaries drain the northern Llano de Albuquerque to the west of Albuquerque and Rio Rancho, whereas the fourth drains northeastern Albuquerque. The three western arroyos are the Arroyos de las Barrancas, Montoyas, and Calabacillas, which drain areas underlain by erodible Santa Fe Group sediments and mantled by eolian deposits that can supply abundant sand and lesser gravel (Connell, 1998). Arroyo de las Barrancas enters the Rio Grande approximately 56 km downstream from Cochiti Dam; its drainage basin is roughly 70 km^2. The arroyo mouth forms a fan deposit at its confluence with the Rio Grande. The channel has been extensively modified upstream with erosion control structures and flood control features. Arroyo de las Montoyas is located approximately 59 km downstream from Cochiti Dam; its drainage basin is roughly 110 km^2. The lower arroyo is straightened and concrete-lined through the town of Corrales to the Rio Grande. The largest of these tributary basins is the Calabacillas drainage basin, which has an area of 220 km^2 (Hawley et al., 1991). Arroyo de las Calabacillas enters the Rio Grande approximately 69 km downstream from Cochiti Dam. This arroyo also drains the sand-rich Santa Fe Group sediments found within the Llano de Albuquerque. The Calabacillas arroyo mouth forms a natural fan deposit at its confluence with the Rio Grande, but just above the confluence the arroyo channel has been extensively engineered.

The AMAFCA North Diversion Channel is the only significant tributary within the study reach that enters from the east. This channel is part of an engineered network of drainage and flood control structures that are used to drain all of northeast Albuquerque and the adjacent Sandia Mountain front. The mouth of the channel is heavily engineered with no observed fan formation, although the Rio Grande channel is unusually wide in the confluence area (Figure 9). The mouth of the channel is located approximately 65 km downstream from Cochiti Dam. The large urbanized drainage area of impervious surfaces and network of concrete-lined channels that makes up this drainage system allows for large discharges into the system during prolonged or intense periods of precipitation.

Figure 9. Oblique air photo, looking east, of the Rio Grande - AMAFCA North Diversion Channel confluence, at Albuquerque, New Mexico. Notice the engineered channel and arroyo mouth at the confluence in addition to the lack of a depositional fan surface at the confluence. The typical wide, shallow, multi-thalweg, island and bar-braided channel planform typical of the downstream half of the study reach is well displayed in this photo.

Bordering fluvial terraces and bank characteristics

Terraces and bedrock outcrops within the study reach may have an influence on local baselevel and channel morphology. Slump blocks may fall into the channel and act as local baselevel controls, but this is unlikely due to the relatively small size of these slump blocks. Also gravelly sediment eroded out of the terrace scarps may contribute coarse bedload material to the system and could have an influence on downstream channel morphology. The active channel of the Rio Grande in the study reach is locally bounded by late Pleistocene fluvial terraces. At the upper end of the study reach, on the west bank above the US 550 bridge, unconsolidated Pleistocene terrace gravels overlie an erosional surface (strath) formed by lateral channel migration at a former higher channel level (Figure 10). The strath surface is about 4 m above the modern floodplain. It is cut on upper Santa Fe Group sediments, termed the Loma Barbon Member of the Arroyo Ojito Formation (Qtob) (Connell et al., 1998). In this area, the Loma Barbon is a poorly sorted, medium to coarse-grained sand with mostly very weak cementation; however, a moderately indurated zone of much stronger cementation about 35-180 cm thick directly underlies the strath surface (Figure 10). Cementation fades out downward through a thin transitional zone to the very weakly cemented underlying sands. The cement is largely calcium carbonate ($CaCO_3$) and is most likely associated with water migrating through the unit during and after the time of erosion of the strath surface. Fluted, streamlined erosional surfaces on the strath surface suggest that cementation may have developed concurrently with formation of the strath, perhaps with seasonal wetting and drying of the Rio Grande paleochannel in this area; it is possible, however, that the shallow erosional scours were formed and preserved in loose or only weakly cemented sand.

Lateral erosion by the present Rio Grande channel has caused undercutting of the cemented layer, during which the friable sands of the Loma Barbon member have been preferentially eroded. This erosion and undercutting has caused toppling and sliding of large slabs and blocks of cemented sand toward the river. A number of these blocks rest along the bank near low-discharge levels of the Rio Grande (Figure 10). I found no evidence of *in situ* cemented sands at river level, however.

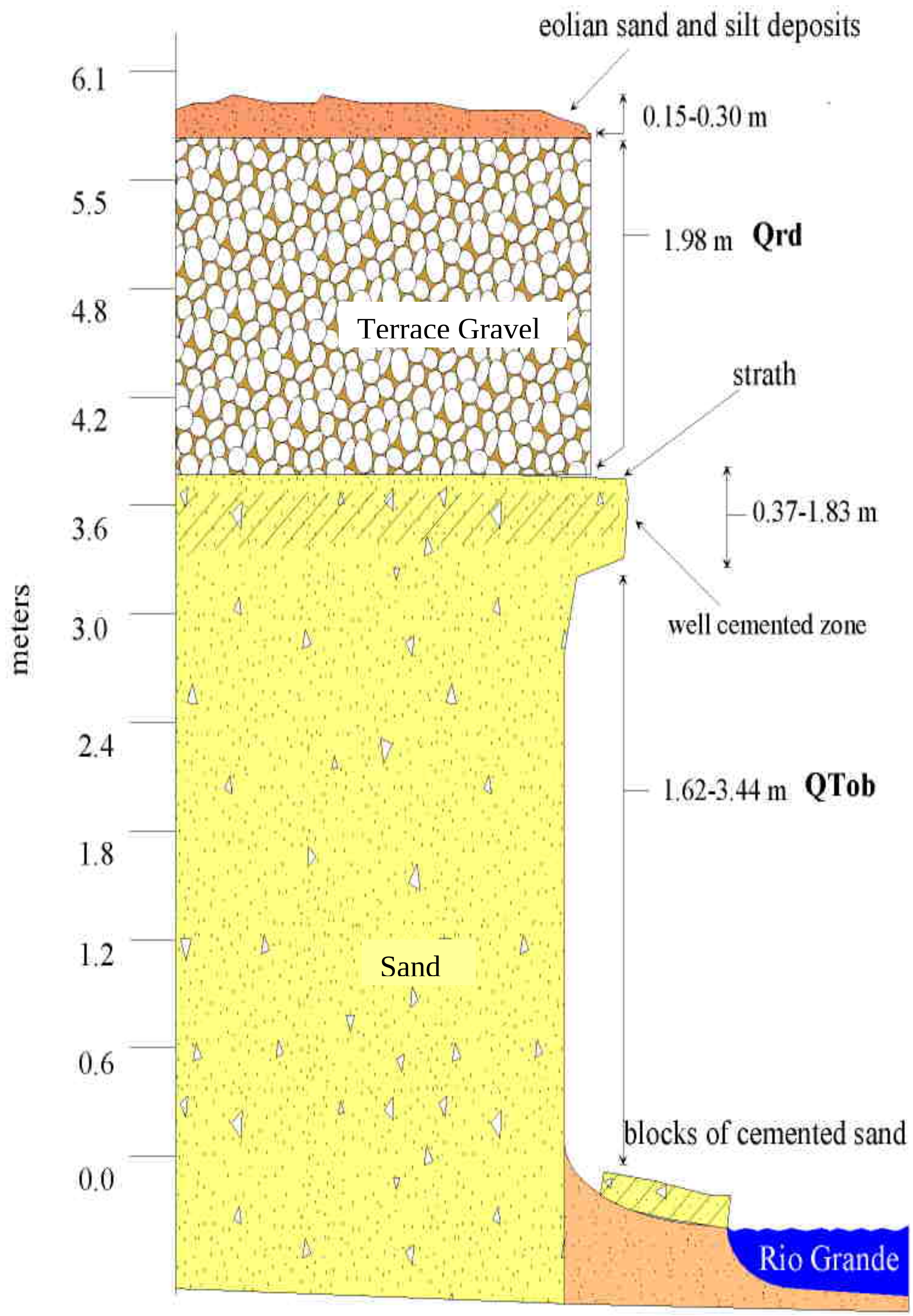


Figure 10 Cross-section of sediments exposed along the west bank of the Rio Grande at Coronado State Monument, Bernalillo, New Mexico.

The terrace gravels overlying the strath were termed the Los Duranes Formation (Qrd) by Connell et al. (1998). Along the river bank exposure the Los Duranes is a sandy gravel approximately 2 m thick; the gravel thickens somewhat westward where higher terrace levels are preserved. The gravel is not cemented, but contains some pedogenic $CaCO_3$ rinds on clasts. Overlying the Los Duranes terrace gravels is a veneer of sand and silt, probably of eolian and locally alluvial origin.

In July, 2001, the bed of the west channel consisted predominantly of gravel, with small dunes of loose sand within the thalweg near the west bank. Although detached blocks of cemented sediments derived from the strath above are common near river level, I did not find evidence of a cemented zone extending into or forming the riverbed. Turbidity and flow depth at the time of the investigation did not allow direct viewing of the bed, but wading across and through most of the reach and digging below the gravel bed surface yielded no evidence of an indurated cemented zone within the channel. The east bank of the west channel is part of a large island and is formed of unconsolidated sand to pebble and cobble gravel of modern age. No cemented sand units or loose blocks of similar material were observed along this bank. Because the strath is approximately planar and parallel to the modern floodplain, but several meters above it, it is unlikely that the strath and associated cemented zone converge with the modern channel bed. Therefore I consider it unlikely that there is a continuous cemented zone underlying the riverbed in this reach. Moderately cemented areas are present in the Loma Barbon Member in other localities, e.g., a plug-like area of cementation just downstream of the water treatment plant effluent channel at river mile 200.2, and other cemented zones below the Los Duranes gravels and their underlying strath between the Bernalillo Bridge and river mile 200.2. A geologic cross-section of Connell et al. (1998) (Figure 11) crosses the Rio Grande within the Coronado monument area and also indicates that exposure

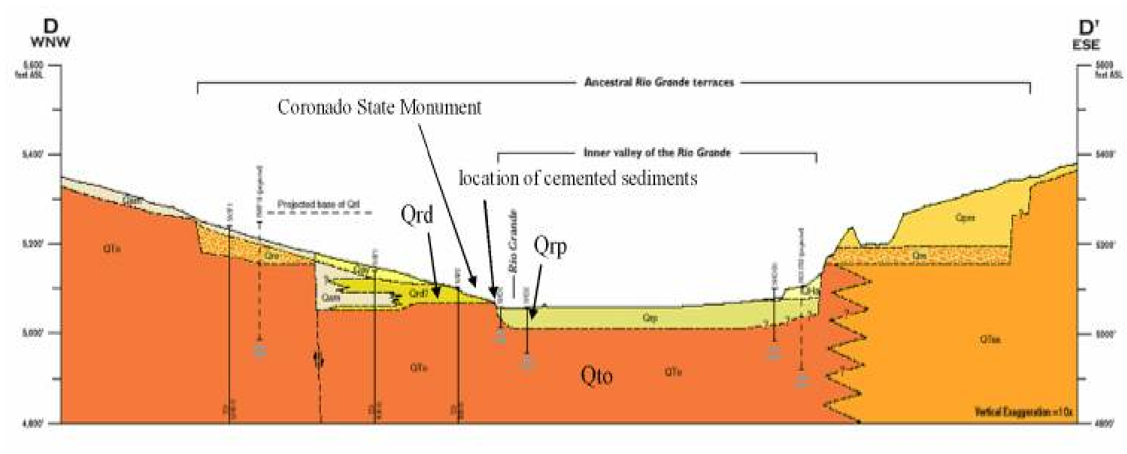


Figure 11 Cross-section from Connell (1998) showing the relationship between modern Rio Grande floodplain deposits (Qrp), Los Duranes Formation (Qrd), and the Loma Barbon member of the Arroyo Ojito Formation (Qto).

of the Loma Barbon Member on the channel bed is unlikely. This cross-section shows that the Arroyo Ojito Formation (and associated locally cemented sediments) lie at depth beneath the modern floodplain, below several tens of meters of aggraded channel fill and floodplain deposits forming the inner Rio Grande valley. This interpretation is supported by drill core data in the Bernalillo Bridge area collected by state agencies (Connell, 1998). Lateral migration of the modern channel system may have cut a short distance over the Loma Barbon Member, so that it very locally underlies channel gravel, but it is unlikely that a broad strath underlies gravel in much of the modern channel. Therefore, cemented sediments probably do not exist to act as a natural grade control structure within the active river channel. However, they may have some influence on the long-term erodibility of the western margin of the Rio Grande inner valley in this area.

Within the study reach the river has cut into the Pleistocene terraces along the west bank at a few other locations. These terraces range in height between 6 and 15 meters and are continuous feature west of the river for more than 65 km. The river begins to cut into these terraces approximately 3 km north of Bernalillo Bridge and continues to meander into and away from the terraces for approximately 6 km, which coincides with Barrancas Arroyo confluence. There are three specific locations where the channel abuts the terraces. The segment north of Bernalillo Bridge is ~ 3 km in length and creates a straight western edge for the channel. The height of the terrace in this location ranges between 10 and 15 meters. The second segment is located approximately 3 km south of Bernalillo Bridge and is ~ 750 meters in length. At this location the channel flows perpendicular into the terrace, turns approximately 80 degrees south and flows along the base of the terrace for approximately 750 meters. The terrace is approximately 15 meters high at this location. The third location is approximately 5.5 km downstream from Bernalillo Bridge and is approximately 10 meters in height. The channel cuts into the terrace at about 45 degrees and flows at the base of the terrace for roughly 500 meters. The southern extent of this terrace segment is cut by the Arroyo de las Barrancas. South of the arroyo the terrace scarp lies farther to the west across the intervening floodplain in the Corrales area. The river begins to cut back into Pleistocene terraces on the west bank south of the study reach near the Rio Grande Nature Center.

Within the Middle Rio Grande valley, the Bureau of Reclamation and the Corps of Engineers consider discharges above 142 m^3/s (5000 ft^3/s) to be channel-forming flows, based on the 1.5-year recurrence interval discharge and field evidence (T. Massong, Bureau of Reclamation, pers. com.). Studies performed by the Bureau of Reclamation and the Corps of Engineers for the “Rio Grande Comprehensive Plan”, indicated that pre-Cochiti Dam channel forming flows for the middle valley of the Rio Grande were around 170 m^3/s (6000 ft^3/s) (Schembera, 1963).

METHODS

Data collected for this study includes grain size analysis from sediment samples collected along the length of the reach, sand depth measurements from within the active channel, bank and vegetated island sediment descriptions, island area changes, a water surface profile, and various channel morphologic parameters including channel width, depth, net downstream incision, and width/depth ratios.

Particle-size Analysis

Bed sediment grab samples were collected along the length of the study reach to obtain a representative sampling of bed sediment variation. Individual grab sample collection was focused on the active channel of the river including the banks, thalweg, sandbars, and smaller sub-channels that branched off the thalweg. Samples were distributed to reflect the relative importance of different textures within a local sub-reach. The following methods were used for the grain size analysis: Following desiccation, a sample splitter was used to obtain about 100 grams of sample, weighed to 0.01 g. Using a standard set of sieves with an interval of 0.5ϕ, the sample was sieved for 15 minutes in a Ro-Tap shaker. Individual sieve fractions were weighed and entered into a spreadsheet to calculate distribution of grain sizes. Using the cumulative distribution curves created in the spreadsheet, median grain size (D_{50}) values were determined and reach-wide and sub-reach grain-size plots were created.

Bed Sand-depth Measurements

Sand depth measurements from within the active channel of the study reach were measured using a 1.5-meter length of rebar, the maximum practical length. The site locations were chosen to represent within-reach variations, from within the thalweg to emergent sandbars. The rebar was hammered into the sandy sediment and when resistance became significant in hard sediments, it was assumed that a gravel deposit was encountered, and a sand depth was recorded. In areas where little resistance was encountered and the rebar was hammered completely into the sediment, a depth of greater than 1.5 m was recorded.

Bank Sediment Descriptions

Detailed bank and vegetated island descriptions were obtained at four locations along the length of the study reach. This work included generalized descriptions of sediment sizes and distributions within the exposure as well as unit thickness. Sedimentary structures, if any, were also recorded along with the distribution of root fragments.

Vegetated Island Area

Vegetated island areas were measured from GIS shape files from air photos provided by the Bureau of Reclamation for the years 1972, 1985, and 1992, and shape files created by the author for this project using the 2001 digitized air photos of the study reach. The vegetated islands were traced and converted into a coverage using ArcInfo, which allowed area calculations to be compared with the area measurements from the Bureau of Reclamation files. I followed the same procedure used by Bureau of

Reclamation personnel, who traced the vegetated perimeter of islands visible on the air photos to create the shape files.

Water Surface Profile

A water surface profile was surveyed along the length of the study reach. This work involved use of an automatic level and 3-meter stadia rod to measure elevations, and a real-time differential GPS system with submeter accuracy for map locations. Because of the lack of accessible benchmarks at the starting point of the survey (Bernalillo Bridge), an arbitrary datum with elevation of 100 m was established at a stable temporary benchmark on a bridge abutment for use during the survey. Future work will tie the survey into known benchmarks at Alameda Bridge and downstream locations. Survey work was conducted at discharges of about 1090 cubic feet per second (ft^3/s) (30.86 cubic meters per second (m^3/s) for the upstream part of the profile and 800 ft^3/s (22.65 m^3/s) for the downstream part. Distances between survey points ranged from approximately 50 m to more than 300 m. Elevations were corrected for Earth curvature and refraction effects. The survey generally followed the thalweg of the river, and point-to-point distances were calculated to plot a long profile. Water surface slopes were also calculated between survey points, and general slopes of subreaches were estimated using standard linear regression.

Channel Morphology and Hydraulic Characteristics

Various channel morphologic parameters were calculated using reach-wide repeated cross-sections from the Bureau of Reclamation. Changes in width, depth, and width/depth ratios were calculated. This study compares pre-Cochiti values (1971) to the most recent post-Cochiti values (2001). For calculations of the average channel depth along the study reach values for 1971, 1980, 1998, and 2001 were used. Channel width and net incision values were calculated directly from the cross-section data. Average depth values were determined using the calculated average depth based on channel area divided by channel width. In order to calculate the cross-sectional area a “bankfull” water surface was estimated using the locations of the floodplain surfaces measured in the cross-sectional surveys, although the floodplain is essentially abandonded at present because of channel incision and reduced peak flows. Values for downstream changes in channel incision where calculated based on yearly changes of average channel depth. The width/depth ratio values were calculated using the standard formula width divided by mean depth.

RESULTS

Bed Sediment Size Variations

Directly after closure of Cochiti Dam in 1973, the study reach experienced a coarsening of bed sediments from fine sand (average D_{50} of 0.21 mm or 2.25ϕ) to medium sand (average D_{50} of 0.27 mm or 1.88ϕ) (Figure 12). This coarsening occurred prior to the gravel- to sand-bed transition zone reaching its current location within the study reach. The coarsening of grain sizes is thought to be a direct result of initial sediment-deprived releases from Cochiti Dam after dam operations went into effect.

A total of 125 bed sediment samples were collected along the length of the study reach. Sediment size terminology used here follows the Wentworth classification (Table 1). Sampling was particularly focused in and around the apparent transition zone between pebble and cobble gravel bed sediments (2-128 mm) dominating the upper reach and fine to coarse-grained sands (0.125-1 mm) of the lower each. The largest clasts (D_{95} of ~64 mm) were located at the upstream end of the reach near U.S. 550, whereas the smallest clasts (D_{95} of ~0.125 mm) were found around the Arroyo de las Montoyas. Median grain sizes throughout the reach range from 64 mm to 0.125 mm. The coarsest median grain sizes (64 mm to 1 mm) are found in the upstream portion of the reach. Downstream of Arroyo de las Barrancas D_{50} grain sizes become significantly finer, but coarse-grained patches remain within the channel (D_{50} of 32 mm to 0.125 mm).

Table 1 Wentworth grainsize classification scale used in this study (from Wentworth, 1922).

Millimeters		µm	Phi (ϕ)	Wentworth size class	
			-20		
	4096		-12	Boulder (-8 to -12ϕ)	
	1024		-10		
	256		-8		
	64		-6	Cobble (-6 to -8ϕ)	
	16		-4	Pebble (-2 to -6ϕ)	Gravel
	4		-2		
	3.36		-1.75		
	2.83		-1.50	Granule	
	2.38		-1.25		
	2.00		-1.00		
	1.68		-0.75		
	1.41		-0.50	Very coarse sand	
	1.19		-0.25		
	1.00		-0.00		
	0.84		0.25		
	0.71		0.50	Coarse sand	
	0.59		0.75		
1/2	0.50	500	1.00		
	0.42	420	1.25		
	0.35	350	1.50	Medium sand	Sand
	0.30	300	1.75		
1/4	0.25	250	2.00		
	0.210	210	2.25		
	0.177	177	2.50	Fine sand	
	0.149	149	2.75		
1/8	0.125	125	3.00		
	0.105	105	3.25		
	0.088	88	3.50	Very fine sand	
	0.074	74	3.75		
1/16	0.0625	63	4.00		
	0.0530	53	4.25		
	0.0440	44	4.50	Coarse silt	
	0.0370	37	4.75		
1/32	0.0310	31	5		
1/64	0.0156	15.6	6	Medium silt	
1/128	0.0078	7.8	7	Fine silt	
1/256	0.0039	3.9	8	Very fine silt	
	0.0020	2.0	9		Mud
	0.00098	0.98	10		
	0.00049	0.49	11		
	0.00024	0.24	12	Clay	
	0.00012	0.12	13		
	0.00006	0.06	14		

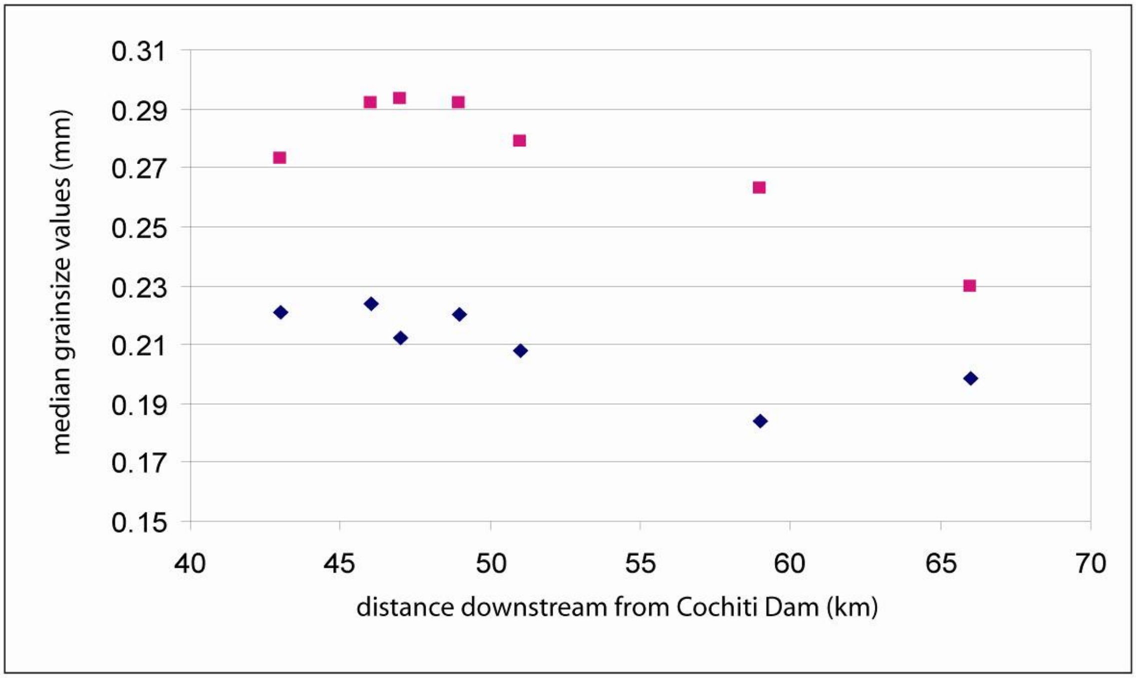


Figure 12 Plot showing the change in average median grain sizes of bed-sediment within the study reach before (pink squares) and directly after (blue diamonds) closure of Cochiti Dam. CO-Line numbers correspond to Bureau of Reclamation repeated survey of cross-section lines within the study reach. All samples on this plot are within the medium to fine-grained sand range. Sediment data was provided by the Bureau of Reclamation.

Downstream of Arroyo de las Montoyas this fining trend continues, but median grain sizes in the gravel range are largely absent. The largest median grain sizes sampled below Arroyo de las Montoyas are no larger than very coarse sand and granules (about 2 mm).

Another trend observed in the grain size data is a reduction in variability of particle size distributions in general within sub-reaches downstream. The most upstream sub-reach around the U.S. 550 Bridge has a range of median grain sizes from 1-64 mm, whereas the most downstream sub-reach south of Paseo del Norte has a range from 0.25-1 mm. Although the upstream sample areas in the reach contain the coarsest grained material, the largest variability with the study reach occurs around the transition zone.

Specifically, the areas of highest variability are found around the two major arroyos within the study reach. The northernmost of these two arroyos, Arroyo de los Barrancas, has a range of median grain sizes from 0.125-16 mm. The southern arroyo, Arroyo de las Montoyas, has a wider range of median grain sizes, from 0.125-32 mm. South of the Arroyo de las Montoyas grain size variability continues to decrease. Near the mouth of the Arroyo de las Calabacillas D_{50} ranges between 0.375 mm and 2 mm (Figure 13).

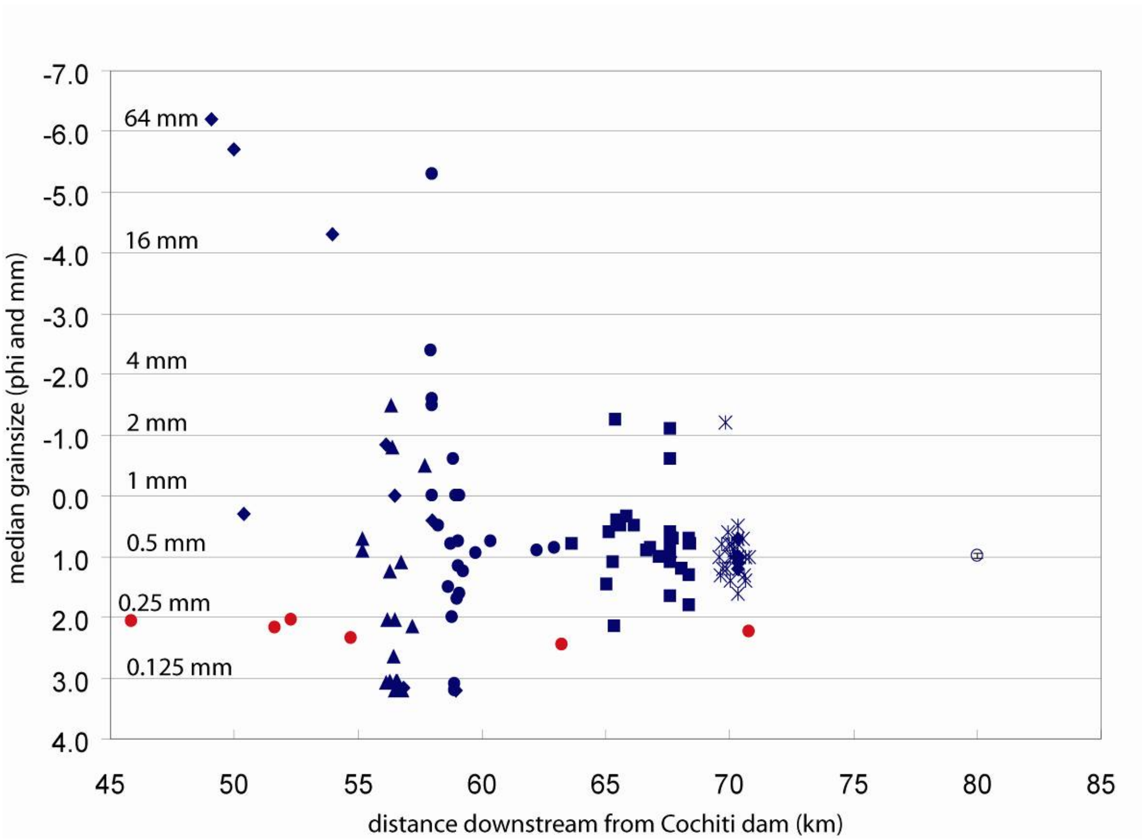


Figure 13 Median grain size values for study reach showing the downstream fining trend and decrease in median size variability through the transition zone between Arroyo de las Barrancas and Arroyo de las Montoyas (blue points). Red points are reach-wide pre-Cochiti dam data. Grain sizes in the study reach range from fine sands to large cobbles. Grainsizes were measured in mm and phi (phi = -$\log_2$d (mm)).

In addition to the decrease in median grainsizes with distance downstream there is a related increase in the degree of sorting of grains (Figure 13). There is a decrease in sorting between the upstream, moderately sorted, gravel dominated reach and the very poorly sorted sand and gravel reach found within the transition zone. Figure 13 also shows that downstream of the transition zone sediment sorting increases and the bedload sediment becomes moderately sorted as the distance downstream of the transition zone increases (Figure 14).

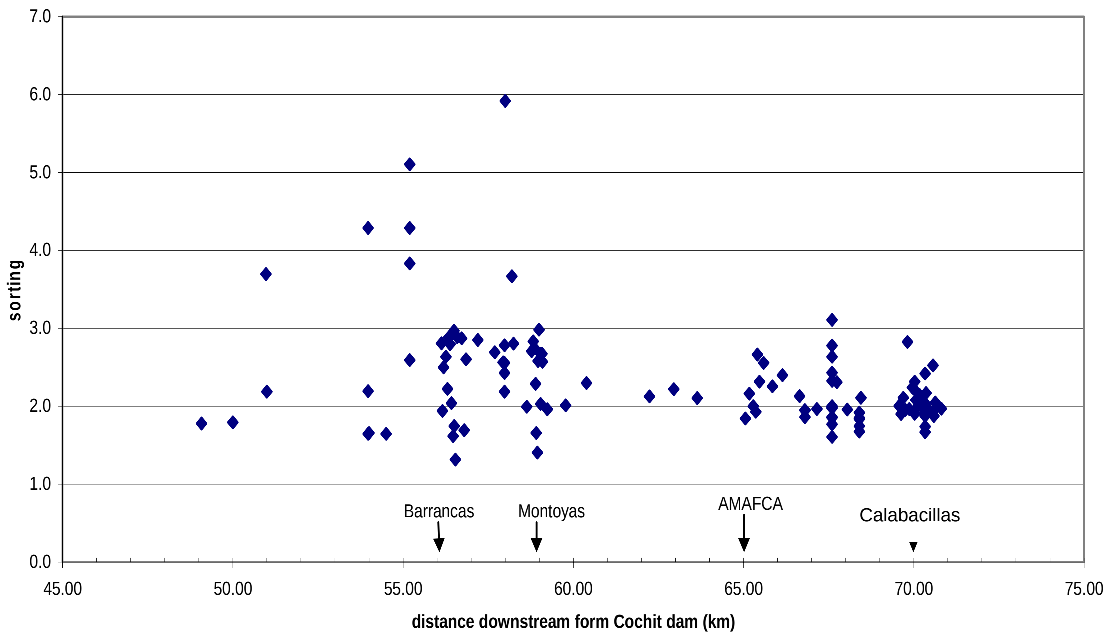


Figure 14 Degree of sorting as a function of distance downstream from Cochiti dam. The most poorly sorted sediment can be found within the transition zone located between Barrancas Arroyo and Montoyas Arroyo.

Bed Sand Depths

Sand depth measurements were taken at 13 locations along the study reach between U.S. 550 and Alameda Bridge. Along the length of the reach sand depths ranged from 25 cm to greater than 155 cm. The shallowest sand depths were measured in the upstream half of the study reach where depth ranged from 25 cm to greater than 155 cm.

Conversely, in the southern half of the study reach all sand depths measured were greater than 155 cm (Figure 15). The amount of channel area composed of sand deposits varied with distance downstream. The far upstream end of the study reach near U.S. 550 Bridge contained approximately 5-10% sand within the high-flow channels, and less than 5% sand within the active channel. These percentages are based on visual estimates performed while in the field. The middle section of the reach around Arroyo de las Barrancas and Arroyo de las Montoyas, based on field observations, was estimated to contained 30% to 60% sand within the active channel and high flow channels. The southernmost section of the reach from Alameda bridge south to Montano bridge is estimated to contain greater than 95% sand within the active channel and high-flow channels. Field observations indicate that a much smaller proportion of the overall channel width in this downstream reach is composed of high-flow channels.

Bank Sediments

Field observations of bank sediments revealed a relatively uniform sandy character to the main east and west banks. Cut-bank exposures were dominated by fine to medium-grained sands, with minor mud lenses distributed within individual sediment layers. The main exceptions to this are areas where the active channel has cut into Pleistocene terrace deposits along its western margin north of the Arroyo de las Barrancas. These ~5-15 m high terrace deposits consist primarily of sand to cobble gravel. Although the gravel deposits are exposed in approximately 45 to 50 percent of terrace scarps, the gravels make up about 10 to 25 percent of the exposed sediment in those locations. Units of pebble and cobble gravel are also commonly found within the vegetated island sediments in the upstream part of the reach. About 10 to 50% of vegetated island sediments are composed of gravel-dominated units, with the most gravel-rich units found upstream of Arroyo de las Barrancas. In general throughout the study reach, pebble gravel was observed within each of the measured vegetated island sections, whereas the measured bank sediment section contained packages of sand-dominated material.

The measured sections ranged in thickness between 100 cm and 155 cm (Figure 15 and Table 2 and 3). Each of the measured sections had between four and seven individual units, which ranged in thickness between 5 cm and 90 cm. The dominant grain sizes found within each of the units were medium to coarse-grained sands. Units with high percentages of gravel had medium to coarse-grained sand matrices. Although sedimentary structures were observed within a few units, they were not very prominent, but included laminar plane bedding, ripple structures, and minor small-scale ripple cross beds. Root fragments were also observed within three of the four measured sections. Based on field observations of bank sediment along the length of the reach, I infer that the described sections are representative samples of the bank and vegetated island sediments found along the length of the study reach. Field observations indicate a dominance of medium to coarse sands and gravel within sediments of vegetated islands in the north of the reach, with the percentages of gravel reducing downstream. In contrast, bank deposits are consistently composed of fine to coarse-grained sands with minor mud lenses along the entire study reach.

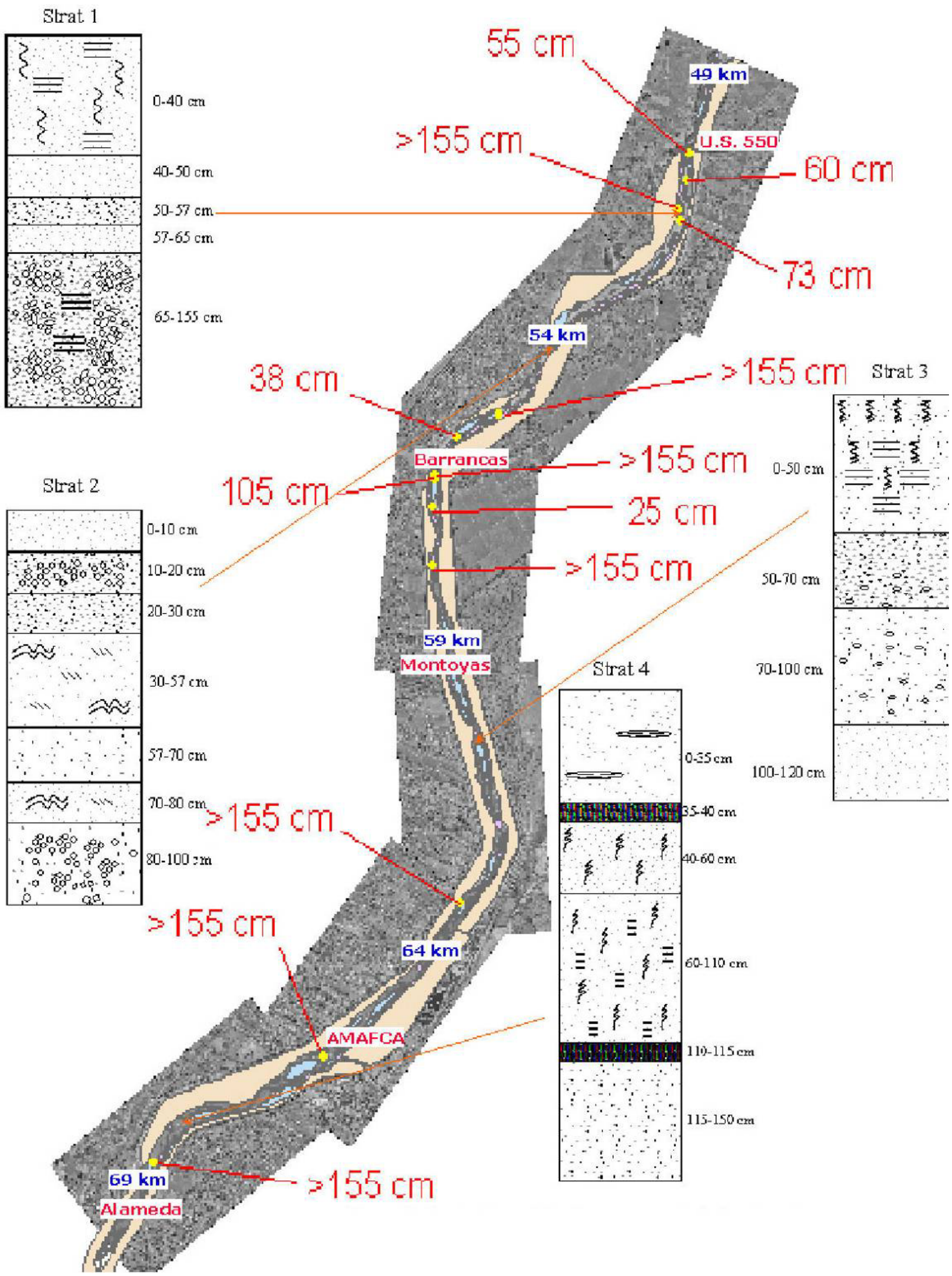
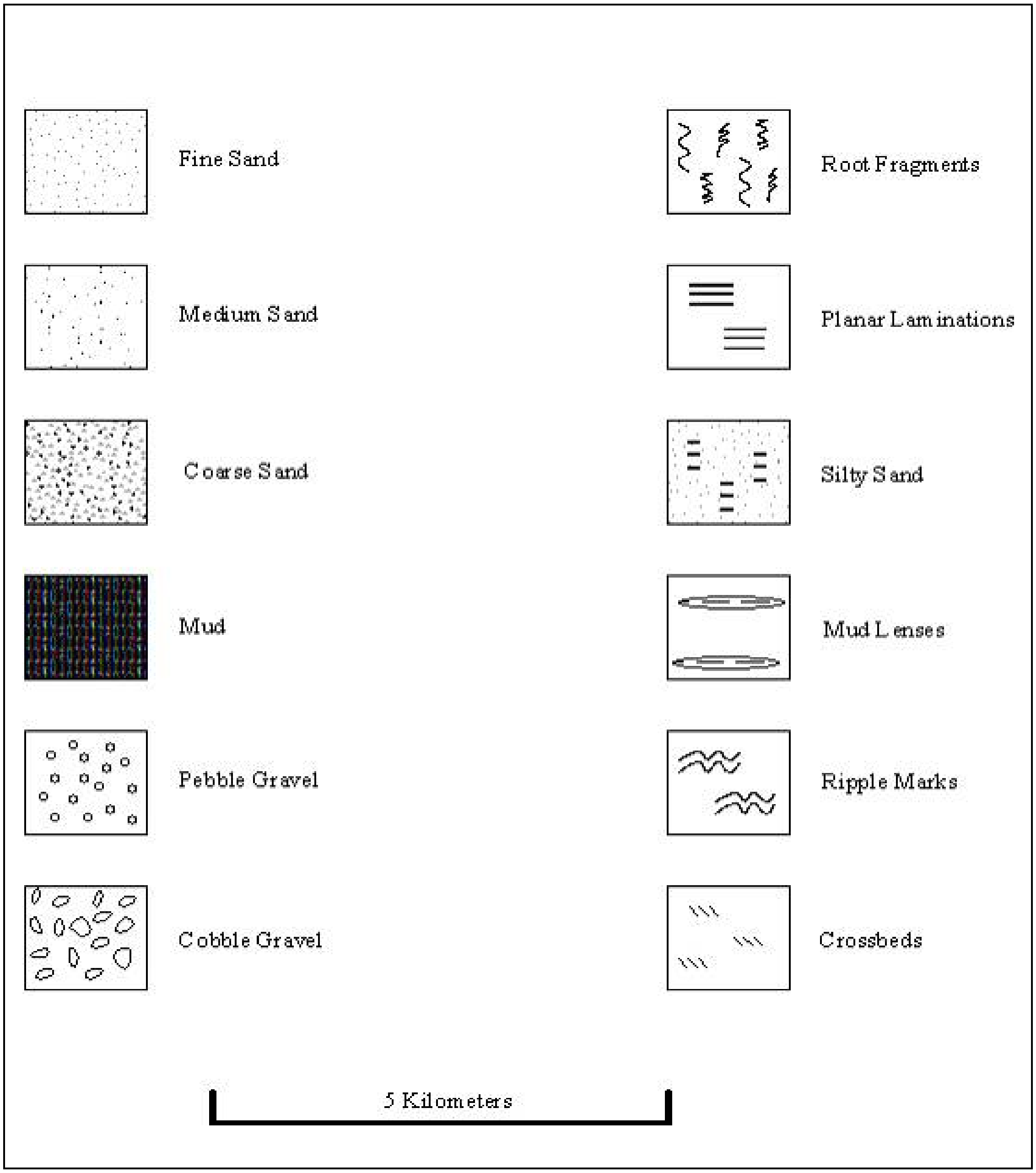


Figure 15 Reach-wide sand depth measurements (cm) and locations, measured stratigraphic sections of bank and vegetated island sediments, and downstream distances from Cochiti Dam (km). See key on following page for explanation of symbols.



Key for Figure 15

Table 2 Measured and described Rio Grande sediments from vegetated islands and bank deposits.

Strat-1	Vegetated island sediments located approximately 200 meters south of U.S. 550 bridge. The thickness of this section was 155 cm and contained five identifiable units.
Depth	**Description**
0-40 cm	fine grained sand, laterally continuous, thickness remains constant. many roots present, laminar bedding visible, possible ripple x-beds
40-50 cm	fine-grained sand, with a high % of silt/clay. Layer is more resistant to excavation
50-57 cm	thin sand layer, medium to coarse grained, no pebbles present laterally continuous
57-65 cm	fine grained sand with a moderate amount of silt/clay. forms cliff in cut.
65-155 cm	coarse sand to cobble gravels, mostly pebble gravels and very coarse sand, laminar bedding visible and possible small scale x-beds.
Strat-2	Vegetated island sediments, located approximately 1200 meters south of U.S. 550 bridge, and had a total thickness of 100 cm with seven identifiable units
Depth	**Description**
0-10 cm	fine-sand, no visible sedimentary structures this layer pinches out to left of measuring tape and thickens to the right of the measuring tape.
10-20 cm	pebble gravel with minor coarse grained sand component. laterally discontinuous
20-30 cm	coarse sand, layer thickness varies laterally. forms sharp contact with layer below it.
30-57 cm	well sorted fine sand, laterally continuous small ripple x-beds visible thickness varies slightly laterally
57-70 cm	medium grained sand laterally discontinuous, thickness varies laterally
70-80 cm	well sorted fine sand, laterally continuous small ripple x-beds visible thickness varies slightly laterally
80-100 cm	pebble gravels in a medium grained sand matrix laterally continuous, although thickness varies

Table 3 Measured and described Rio Grande sediments from vegetated islands and bank deposits.

Strat-3	Vegetated island sediments located approximately 1000 meters south of the Arroyo de las Montoyas. This section was 120 cm thick with four identifiable units.
Depth	**Description**
0-50 cm	medium to fine grained sand, laterally continuous, planar laminations, small roots in upper 30 cm.
50-70 cm	medium to very coarse sand, some pea size gravel (<5%) gravel found at 69-70 cm depth.
70-100 cm	medium to coarse sands, some pebbles interspersed within unit (<7%).
100-120 cm	fine to medium sands, no pebbles, no sedimentary structures, laterally continuous.
Strat-4	Bank sediments located approximately 400 meters north of Alameda Bridge; its total thickness was 150 cm and had six identifiable units.
Depth	**Description**
0-35 cm	fine to medium grained sand, with minor mud lenses hardest layer of bank sediments, possibly due to precipitation Infiltrating into ground at site, fine grained, hard to determine composition of grains
35-40 cm	5 cm thick dark brown mud layer
40-60 cm	very fine grained sand, ~ 20 cm thick, poorly sorted sub-angular to sub-rounded grains, reddish brown, many root fragments
60-110 cm	Sandy silt/clay. Rich in organics, many roots throughout layer, gradually coarsens upward into fine sand sand within the clay is fine to very fine grained becomes dominantly fine grained at 60 cm.
110-115 cm	5 cm thick mud layer, this unit is hard and well compacted brown to black in color
115-150 cm	unconsolidated medium grained sand, poorly sorted angular to sub-rounded grains, sand body appears to have been oxidized

Vegetated Island Areas

Total vegetated island area along the study reach has changed significantly since 1972 (Figure 16). In 1972, two vegetated islands with a combined surface area of 0.010 km^2 were mapped within the study reach. In 1985, 12 years after the closure of Cochiti Dam, the number of vegetated islands had increased to 12. These islands had a combined surface area of 0.056 km^2. During the 7-year period between 1985 and 1992, the number of vegetated islands increased to a total of 99, and the total surface area increased to 0.386 km^2. The most remarkable increase in total vegetated island surface area occurred between 1992 and 2001. During that period the total number reached 144 vegetated islands within the reach with a total surface area of 0.896 km^2.

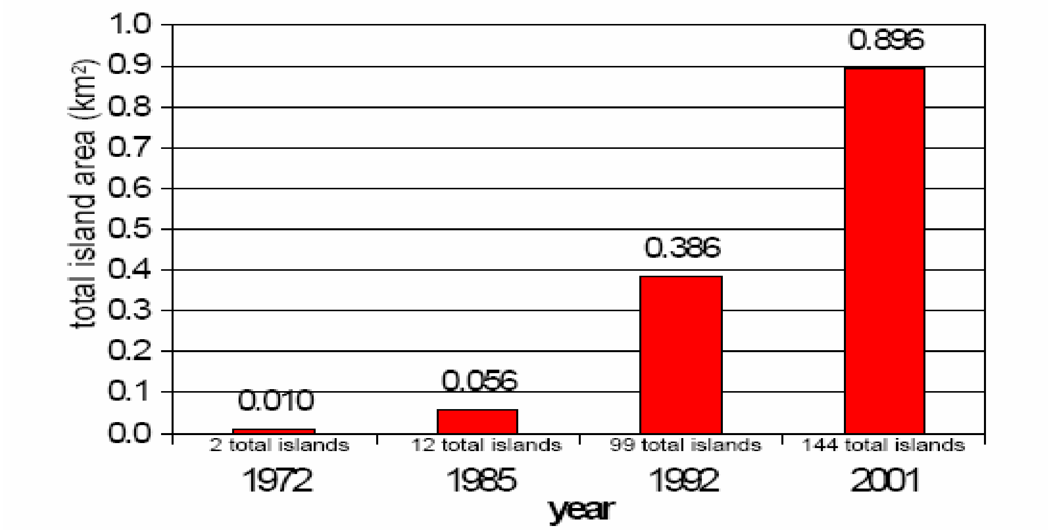


Figure 16 Changes in vegetated island areas since closure of Cochiti Dam. Island areas were calculated from shape files created in a GIS by Bureau of Reclamation personnel and in this stud

Water Surface Profile

The surveyed water surface profile indicates that the Rio Grande between Bernalillo Bridge and the Arroyo de las Montoyas has an overall slope of 0.0008. Below this arroyo to near Alameda Bridge, overall slope increases slightly to 0.0009. There is also a slight decrease in slope for ~200 m above the Arroyo de las Barrancas. In this location slope above the arroyo was measured at 0.0007, whereas adjacent to and directly downstream of the arroyo for ~100 m slope increases to 0.0008, and higher-velocity flow over the bar built by the arroyo is apparent. There is also a slope decrease above the Arroyo de las Montoyas, but a slope increase below is not apparent in the field, and surveys done at different discharges across this area prevent close delineation of slope changes (Figure 17)

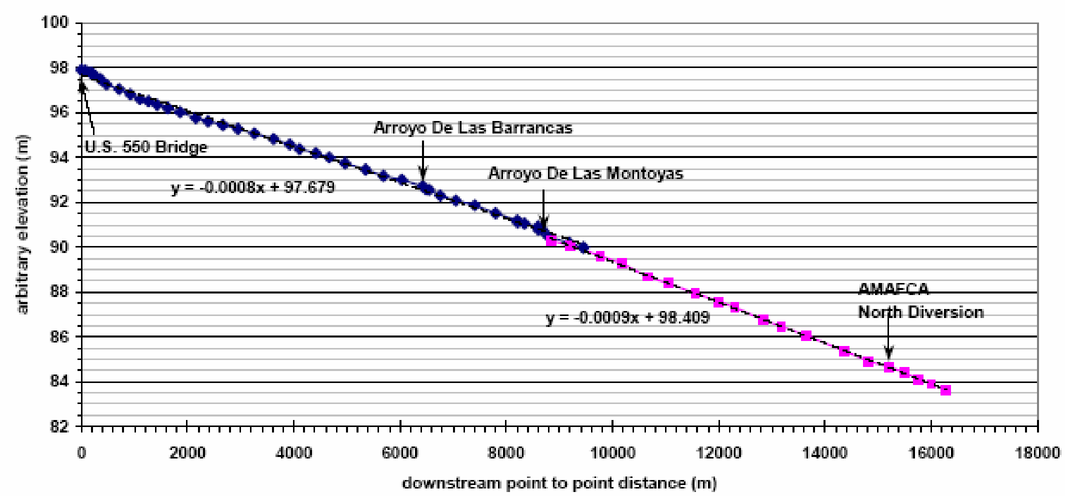


Figure 17 Long profile of study reach from water surface leveling survey data. Primary survey map locations (blue diamonds) were recorded using a differential GPS unit with sub-meter accuracy. The secondary survey map locations (pink squares) were recorded with a handheld Garmin 12 GPS unit with meter accuracy. Linear regression equations of the form y = mx + b were calculated to determine the slope of each survey; where m = the slope and b = the y-intercept

Channel Morphology

The active thalweg channel width within the study reach varies dramatically along the 25 km; upstream the low-discharge channel width is typically between 20 and 30 m and dominated by a single deeply incised thalweg. The total width of the upstream channel between the floodplain banks ranges between 128 meters and 268 meters. In the southern section of the study reach the channel is ranges in width between 108 meters and 268 meters, with a shallow, multiple thalweg planform. The low-discharge channel width is

Figure 18 Visible channel planform transition zone: a single threaded, locally island braided channel with a deep, fast flowing thalweg (upstream of Barrancas Arroyo) undergoes a transition into a wider, multi-threaded, island and bar-braided channel with shallow, slower flowing multiple thalwegs (downstream from Montoyas Arroyo).

equal to the total channel width as measured between the floodplain banks. There is a general decrease in total channel width as distance downstream increases (Figure 19).

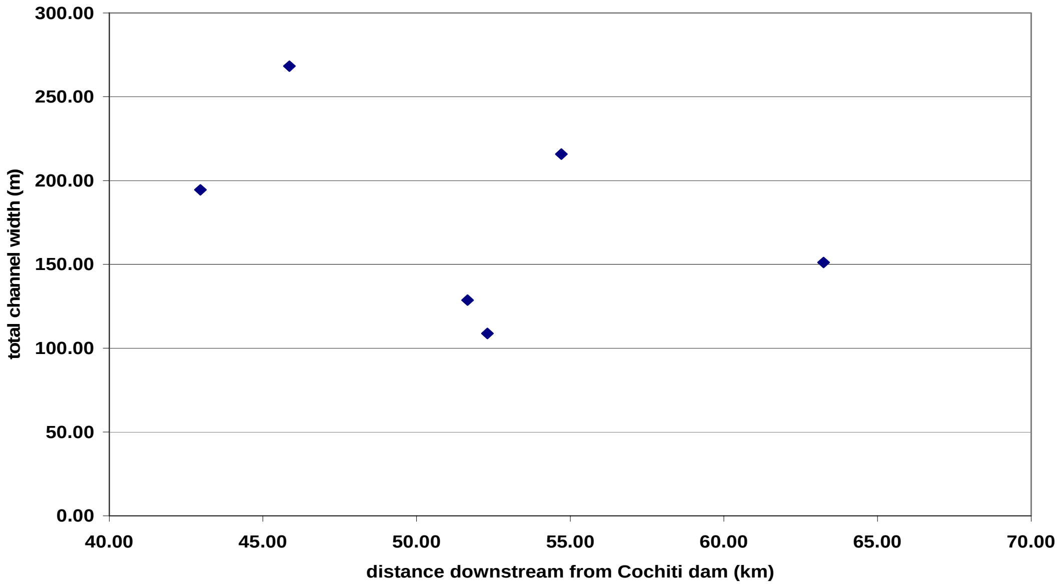


Figure 19 Total channel width change versus distance downstream from Cochiti Dam.

The decrease in total channel width with distance downstream contrasts with an increase in the width/depth ratio as downstream distance increases. The upstream reach has a range of width to depth ratios between 54 and 180. With the exception of the value at 180 measured at CO-30, each upstream width to depth ratio was found to be below 100. Downstream the width to depth ratios range between 104 and 289 (Figure 20).

Between the Arroyo de las Barrancas and the Arroyo de las Montoyas there is an observable change in channel morphology. A single-threaded, locally island-braided channel with a deep, fast-flowing thalweg undergoes a transition into a wider, multi-threaded, island and bar braided channel with shallow, slower-flowing multiple thalwegs (Figure 18).

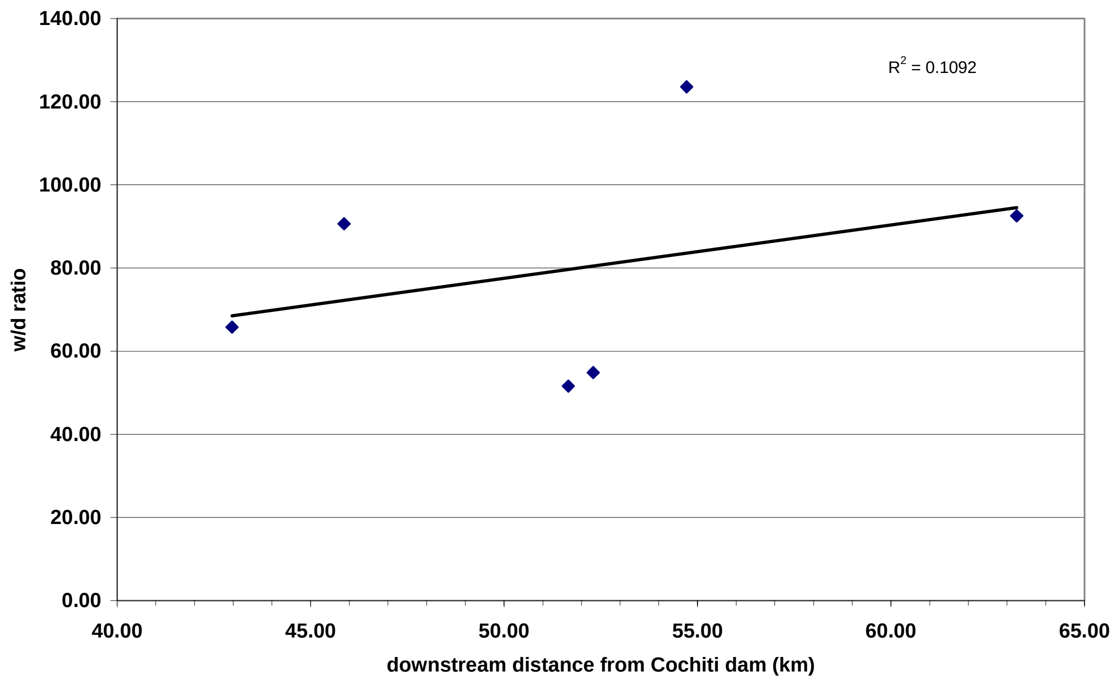


Figure 20 Changes in total channel width to depth ratio as distance downstream from Cochiti dam increases.

Upstream, low discharges below 2000 ft^3/s (56.63 m^3/s) are contained within the dominant single threaded channel. With increased discharges various elevated channels become activated and create a multi-threaded, island-braided planform. Below Arroyo de las Montoyas the multi-threaded island- and bar-braided planform exists at low flows and does not change as dramatically with discharge. At flows < 400 ft^3/s (11.32 m^3/s) more sand bars become exposed and increase the number of channels present within the southern section of the reach. Flows above 400 ft^3/s (11.32 m^3/s) combine some of these minor thalwegs, but the number of vegetated islands and recently stabilized sand bars south of the Montoyas Arroyo keep the multi-threaded planform in place.

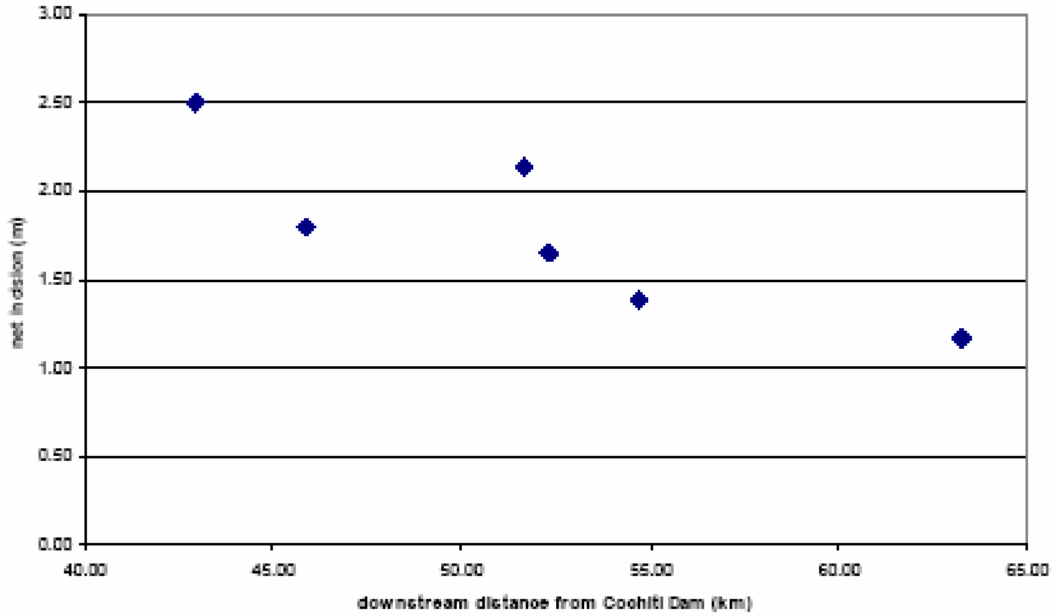


Figure 21 Net incision as a function of distance downstream from Cochiti Dam through the study reach. Differences between 1972 average bed elevations and 2001 average bed elevations at Bureau of Reclamation cross-section lines were calculated to determine amount of net incision.

Channel incision over the last 30 years has created an elevated and abandoned floodplain along the entire length of the study reach. Net channel incision calculated from the differences between 1972 bed elevations and 2001 bed elevations from within the reach ranges between about 2.5 m upstream to 1.2 m in downstream (Figure 21). Repeated cross-section, CO-29, measured approximately 20 meters upstream of U.S. 550 bridge shows the transformation of the upstream study reach from a wide and shallow (high w/d ratio) channel into a deep and narrow (low w/d ratio) channel configuration. This pattern of incision is consistent with other locations within the upstream half of the study reach. The 1998 cross-section also shows a large vegetated island which has formed at this location since the closure of Cochiti Dam (Figure 22). Repeated cross-section, CO-34, measured roughly 30 meters upstream of Alameda bridge records the level of channel degradation which has occurred at this location at the downstream end of the study reach (Figure 23). This pattern is consistent with other locations within the downstream half of the study reach.

Channel incision along the length of the study reach has not progressed at a uniform rate along the length of the study reach. Incision rates were calculated for the upstream reach, which has experienced the greatest amount of incision (Figure 24). Since closure of Cochiti dam the fastest rate of incision calculated was over the 9 year period between 1971 (2 years before dam closure) and 1980. During this period the upstream reach, around Bernalillo Bridge, incised 0.7 meters which translates to a rate of approximately 0.07 meters per year. The 18 years between 1980 and 1998 experienced a significant decrease in incision rates. During this period the upstream channel incised 0.5 meters which translates to a rate of 0.027 meters of incision per year. Between 1998 and 2001 the study reach experienced very little incision. The upstream reach incised approximately 0.1 meters during this three-year period. This translates to a rate of 0.03 meters per year, which is slightly higher than the rate calculated for the previous period of record 1980-1998 (Figure 24).

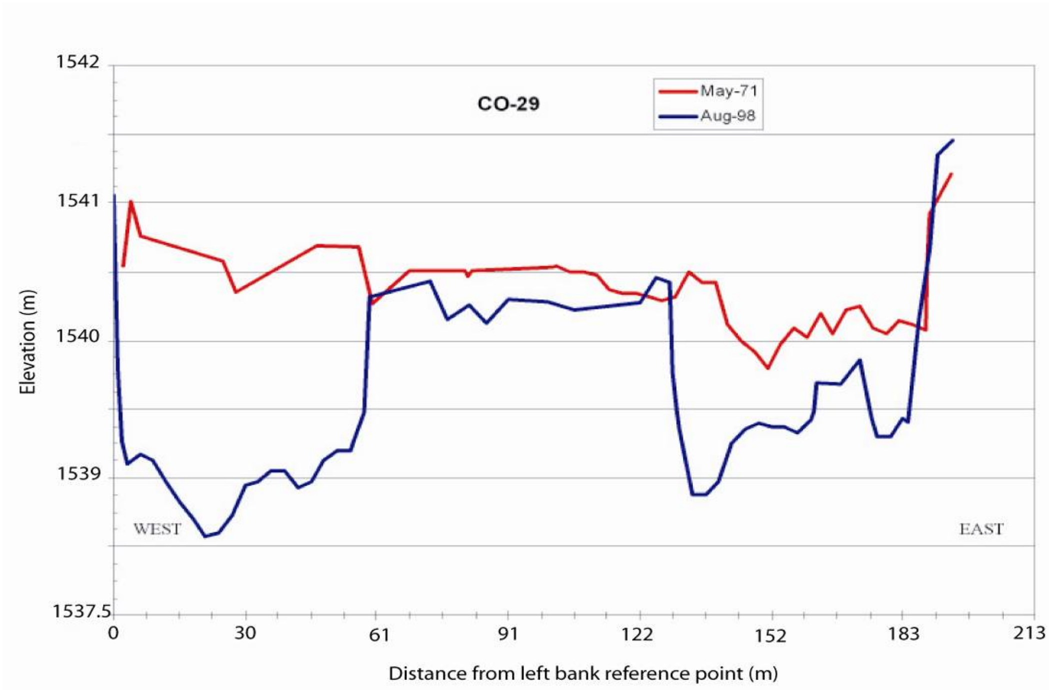


Figure 22 Record of total channel change for a 27-year period (1971-1998) at Bureau of Reclamation cross-section CO-29, located ~20 meters upstream of U.S. 550 Bridge. Notice the significant change in cross-sectional area and the formation of a vegetated island within the middle of the channel at this location

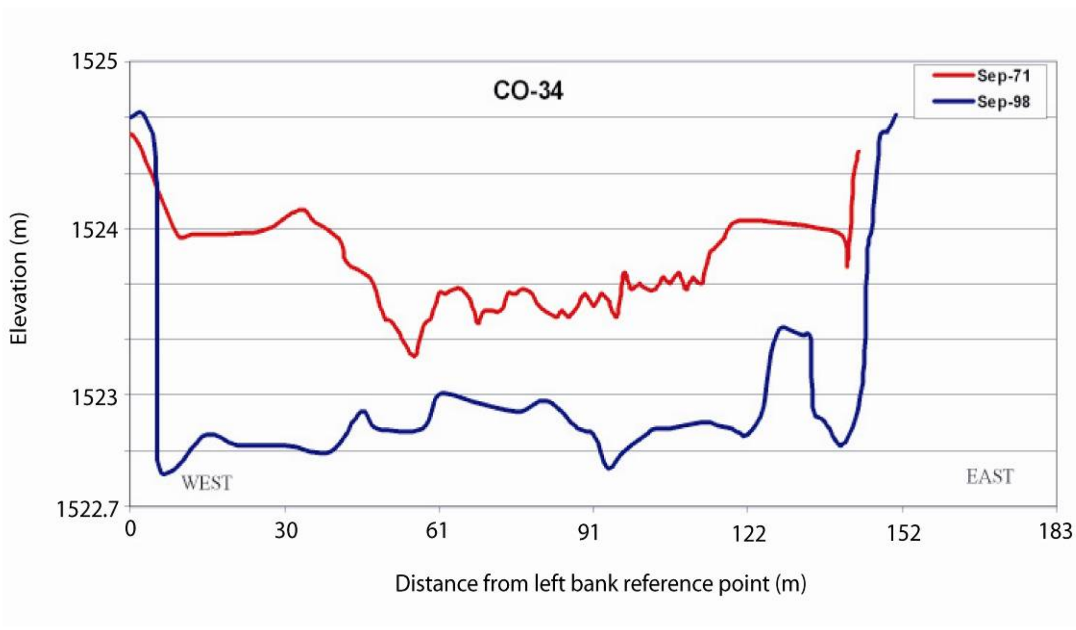


Figure 23 Record of total channel change for a 27-year period (1971-1998) at Bureau of Reclamation cross-section CO-34, located ~30 meters upstream of Alameda Bridge. Although the channel has incised a maximum of about 1.2 meters, at this location the channel cross-section has retained its general morphology.

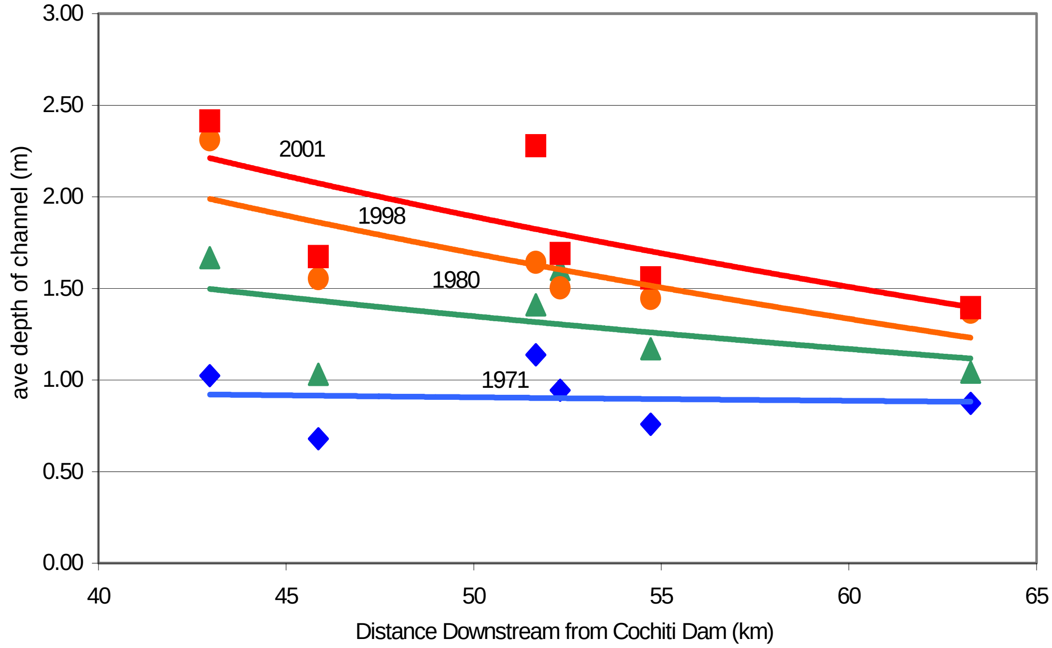


Figure 24 Increase in average channel depth below adjacent floodplain surfaces with distance downstream between the years 1971 and 2001. Differences in channel depth between years of record were used to calculate rates of incision for the upstream reach.

ANALYSIS AND INTERPRETATIONS

Bed sediment variations within the study reach can be attributed to several factors. The relative abundance of gravels within island sediments compared to the gravel-poor sandy bank sediments with very little gravel suggest that a significant amount of gravel has moved into the reach since closure of Cochiti dam. The island gravels may in large part represent coarser bed sediment transported into the study reach because of post-dam channel incision upstream. At least some gravelly bed sediments within the reach are likely the result of winnowing of finer-grained sediment with channel incision and resulting development of a gravel lag. The scarcity of gravel in the main east and west banks along the entire reach and the lack of shallow gravel deposits at shallow depth within the bed, however, suggest that gravel is relatively rare in pre-dam floodplain deposits. Nonetheless, present gravelly channel deposits may be the result of both processes.

Tributary inputs have also likely played an important role in bed sediment characteristics in the study reach. Leopold (1946) described a September 1941 thunderstorm that caused the Arroyo de las Calabacillas to flood at an estimated 10,000 ft^3/s (283 m^3/s). Discharges for the Montoyas and Barrancas arroyos were estimated at 2000 to 4000 ft^3/s (57-113 m^3/s). A large fan deposit at the mouth of the Calabacillas arroyo was estimated by Leopold (1946) to contain almost 150,000 m^3 of sediment, composed mostly of sand, although this flood also deposited some large boulders. A much greater volume of sand entered the Rio Grande channel and was carried downstream. This event, although uncommon, nonetheless illustrates the potential of the large arroyos draining the northern Llano de Albuquerque to episodically contribute large volumes of sandy sediment to the Rio Grande.

The transition zone between coarse and fine-grained material has progressed downstream since dam closure into its current position within the study reach. Lagasse (1981) illustrated a fairly abrupt grain size transition zone located at about river kilometer 35 (distance downstream from Cochiti Dam) in 1980, close to the mouth of the Jemez River (a significant source of sediment prior to damming). The present transition is more diffuse, but I estimate its position to be between river kilometer 51 and 55. This 4 km range is appropriate since field observations do not indicate an abrupt change in grain sizes. The 16 km of downstream progression over the past 23 years translates into a rate of about 0.7 km/yr since 1980, which is significantly slower than the rate of 5 km/yr originally measured by Lagasse (1980) between 1973 and 1980. A rate of downstream progression of coarsening calculated by a second method plotting the year and downstream location where the median bedload grainsize was greater than 2 mm (Figure 25). This is the point where the channel is assumed to have gravel-dominated bed sediment. Using standard linear regression, a rate of 2.14 km/yr was calculated from Figure 25. Although the data in Figure 25 shows a positive correlation the scatter of the data points indicates that the >2 mm transition was, at times, recorded at multiple locations during the same year. This suggests that the location of the >2 mm median grainsize transition may not be a good indicator for transition zone location along the study reach.

It is unknown if the grain size transition zone is currently moving downstream, and if so, at what rate. It may presently be in a static state due to the drought currently affecting the region. An increase in precipitation would increase flows within the study reach and potentially reactivate the downstream progression of the transition zone. The transition zone may also simply be moving too slowly to directly observe any significant change given the short period and limited data of this study.

According to Williams and Wolman (1984), movement of this coarsening front will likely slow until a static transition zone develops, which may be strongly influenced by tributary sediment inputs. The change in median grain size variability occurs between the Barrancas and Montoyas arroyos. This suggests that the infrequent sediment inputs from these two main arroyos may in part control the present location of the transition zone. Grain size analysis at these locations indicates that grain sizes mainly between 128

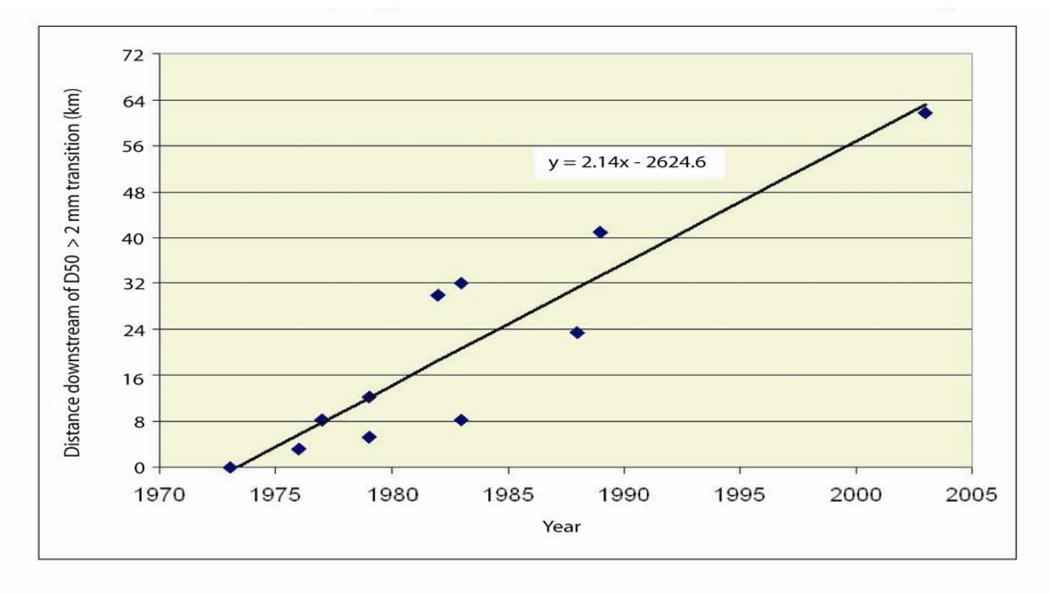


Figure 25 Plot of distance downstream of the D_{50} > 2mm transition over time since the closure of Cochiti dam in 1973. Data compiled from Harvey, 2003 and this project.

mm and 0.125 mm are being introduced into the system, dominated by very coarse to medium sand (2 - 0.25 mm). Although granules are found downstream to Alameda Bridge, field observations suggest that pebbles and cobbles (4-256 mm) may not be actively transported south of the Arroyo de las Montoyas. The granules could be an indication that channel coarsening to include significant gravel bed sediments is beginning to progress south of the Arroyo de las Montoyas.

The aggradation of sediment at the arroyo mouths is observed within the water surface profile as the changing of the slope at both arroyo locations. The slope changes at the Arroyo de las Barrancas and the Arroyo de las Montoyas indicate that some coarse sediment remains near the arroyo mouths and locally controls slope. At typical present discharges (<1500 ft^3/s or <42.47 m^3/s), the system is unable to remove the coarser fraction of introduced sediment, causing reduction of slope above the tributary fan. Downstream of the sediment sources, water surface slope increases as water flows over the coarse sediment accumulation.

Above the Arroyo de las Barrancas pebble and cobble gravels are the predominant grain sizes within the active channel and thalweg. The majority of sand present within the overall active channel area above Arroyo de las Barrancas is being stored in high-flow channels along with additional pebble and cobble gravels. Based on field observations it is estimated that 95% of active channel bed sediment are pebble and cobble gravels. Stored sediment within high-flow channels consists of approximately 65% gravel and 35% sand within the upstream areas of the study reach. Downstream of the Arroyo de las Montoyas channel bed sediment composition is estimated at 95% sand and 5% granules and pebble gravels. Sediment stored within vegetated islands south of Arroyo de las Montoyas is estimated at approximately 85% to 90% sand with the remaining sediment composed of granules and pebble gravels. Using field observations of discharge and stage, I estimate that a discharge of over 2500 ft^3/s (~70 m^3/s) would be required in order to move the sand stored within the high-flow channels downstream. This would flood the high-flow channels and mobilize the sand-sized particles. A significantly higher discharge (5000-7000 ft^3/s or 142-198 m^3/s) would be required to mobilize the gravels stored within the high-flow channels.

The increase in total number of vegetated islands and island surface area can also be attributed at least in part to controlled discharges from Cochiti Dam. As flows are reduced and incision continues downstream, water becomes confined to a smaller channel area, and more stable areas of sediment in storage become available for plant colonization by tamarisk, Russian olive, and willows. Plants stabilize large areas within the active channel zone and promote further colonization along the margins of vegetated islands and at extreme low flows on top of emergent sand bars. When discharges remain low (<1500 ft^3/s (42 m^3/s)) throughout the year, more emergent sand bars are becoming stabilized which further decreases the availability of transportable sediment.

Changes in channel morphology downstream from U.S. 550 are also likely to exist mostly because of dam effects and current channel bed sediment conditions, as opposed to pre-dam downstream changes. The single-threaded dominant channel planform, low width-to-depth ratios and higher incision rates found in the upstream reach are a direct result of the sediment trapping upstream of Cochiti dam which provided the catalyst for the locally armored condition and gravel-rich sediment characteristics found within the active channel. The armoring of the channel and the absence of easily erodible sands within the banks exposed to low flows, in combination with the reduced post-dam flood discharges jetty jacks and bank vegetation inhibits lateral channel migration and maintenance of a braided channel planform. Jetty jacks and vegetation along the channel banks create turbulence within the flow along the channel margin. The disrupted flow promotes sediment deposition and creation of stabilized surfaces within the active channel. This process inhibits the maintenance of a braided channel planform and effectively reduces lateral channel migration within the active channel of the river.

Channel morphology is significantly affected by changes in vegetated island areas, sediment inputs from tributaries, bed sediment characteristics and discharge, but the reduced bedload may be the dominant factor driving upstream channel morphology within the upstream reach. With the construction of Cochiti dam flows became highly regulated and large amounts of sediment became trapped upstream of the dam. The clear water released from the dam led to the immediate degradation and local armoring of the channel downstream from the dam (Lagasse, 1980). The continued clear water releases, in addition to the lack of bedload sediment coming from upstream, has caused channel degradation to progress downstream into the study reach. Besides the elimination of upstream sediment inputs and flood peaks from the annual hydrograph, flow regulation also increased the baseflow discharge during the year. Although there is some sand being stored within the channel of the lower portion of the upstream reach, I infer that there is simply not enough sand being delivered to the channel in the post-dam period to keep the higher, more effective flows from moving the great majority of it downstream.

Significant sandy sediment may be discharged into the system from the tributaries. Specifically, within the watersheds of the Arroyos Barrancas and Montoyas, highly erodible Santa Fe group sediments and younger eolian deposits contribute large amounts of sediment when a storm creates enough runoff to discharge into the mainstem Rio Grande. Although the potential importance of these arroyo inputs is recognized, there are currently no data on amount of sediment discharged into the system during any event following the construction of Cochiti dam, and such inputs would be also difficult to measure in the future. The visible change in channel planform south of the two main arroyos suggest that these inputs of sediment are important controlling factors of downstream channel morphology. In combination with sediment trapping by Cochiti dam, tributary sediment inputs are probably more important controlling factors on channel morphology than the current discharge regime. Alternately, it may be that the sands within the downstream reach have not been flushed through the study reach but will be by the downstream progression of the transition zone.

CONCLUSIONS AND SUMMARY

One of the primary foci of this study of post-dam downstream changes is bed sediment grain sizes. Three hypotheses were formulated and tested. The first proposed that the current bed sediment texture within the study reach is little changed from pre-dam sediment conditions and reflected the expected downstream fining of grain sizes as distance from primary gravel sources decreases. The sediment data do not support this hypothesis. The pre-dam bed sediment median grain size was fine sand along the entire length of the study reach (Figure 12). The coarsening of bed sediment, from fine to medium sand, occurred directly after dam closure, along the length of the study reach, and dramatically increased in the 30 years following.

The second sediment hypothesis is that the gravel bed found in the upstream reach is a lag deposit composed of gravels present within the floodplain sediments prior to channel incision. Although minor pebble gravels have historically been observed within the pre-dam channel, there is little evidence of gravel found within the modern floodplain sediments even in the upstream reach. This suggests that pebble and cobble gravels currently found within the active channel were not present in major quantities within the study reach prior to the 1940's, when the observed floodplain sediments were deposited.

The third hypothesis tested suggested that the gravels found within the study reach were primarily transported downstream from incising reaches to the north into the study reach. The data collected for the study most strongly support this hypothesis. The lack of gravel within the bank sediments combined with the presence of gravel within the younger vegetated island sediments suggests that gravel was introduced into the study reach after the closure of Cochiti Dam. Following closure of the dam channel incision, coarsening of bed sediment and formation of vegetated islands began to occur. In addition to the introduction of gravel into the study reach, bed sediment coarsening can also be attributed to the selective transport of sand downstream into the lower and beyond the study reach. Upstream incision and movement of gravel downstream into the study reach was recorded within the stored sediment, which ultimately stabilized and formed into the vegetated islands. Gravel within the vegetated island sediments decreases in size and volume with distance downstream which indicates that the effects of upstream incision has not completely translated downstream through the length of the study reach.

This study characterizes the geomorphic and bed-sediment transition zone within the study reach currently located between the Arroyos Barrancas and Montoya. In the future (1) sediment inputs from tributaries will slow or halt the downstream progress of the zone through the reach, or (2) clear water releases throughout the year from Cochiti Dam will continue to facilitate movement of the zone downstream. This project could not provide an answer to this question, but the current location of the transition zone located between Barrancas Arroyo and Montoyas Arroyo suggests that the sediment inputs from these two arroyos may have slowed the migration of the transition zone. Further study is required to determine if the transition zone is static or if the downstream movement will continue, and at what rate.

The clear water releases from Cochiti dam are important factors that contribute to current channel morphology, channel degradation, and increases in vegetated island areas. With recent drought conditions, it may be that flows through the study reach are not large enough to force the downstream progression of the transition zone. An increase in peak flows through the study reach would potentially facilitate the downstream movement of the transition zone. A decrease in the sporadic sediment inputs from Barrancas and Montoyas Arroyos could also potentially promote the downstream progression of the transition zone.

This project has shown that Cochiti Dam has affected the study reach in a number of ways. Bed sediment along the length of the study reach has progressively become coarser and the number of vegetated islands and associated stabilized surfaces has increased dramatically since the closure of Cochiti Dam. The development of a transition zone between Arroyo de las Barrancas and Arroyo de las Montoyas delineates an upstream reach and a downstream reach. The upstream reach is characterized by coarse-grained bed sediment (pebble and cobble gravel) and a deep, narrow, mostly single-threaded channel planform that becomes island-braided only at higher flows. The downstream reach is characterized by medium and coarse sand bed sediment and a shallow, wide, multi-threaded bar and island-braided channel planform. Sediment inputs from tributaries are probably important controls on grain size distributions and water surface slope changes within the study reach. The current rate of downstream progression of the coarse to fine grained bed-sediment transition zone is unknown. At higher discharges the grain size transition zone could possibly continue movement downstream. Continued channel incision and decreased flood peaks will continue to increase the surface area of bars and islands available for plant colonization including by tamarisk, Russian olive, and willow. This will further reduce the amount of stored sediment available for downstream transport at high discharges. Increased channel incision will also promote continued downstream formation of a dominant single-threaded low-flow channel, and decreased flow frequency in and abandonment of higher multiple channels.

APPENDICES

Appendix A Reach-wide sieve analysis data

Spreadsheet Information
Individual sample sets are delineated by solid lines.
Dashed lines are used to break up larger sample sets into managable subsets.
Sieve size in mm are located in the first column, followed by phi size in the second column.
Values are percentages of total fraction sieved

Alameda 2002

sieve mm size	phi size ♦	AN-1	AN-2	AN-3	AN-4	AN-5	AN-6	AN-7	AN-8	AN-9	AN-10	AN-11
8	-3.0	0.00	5.57	0.00	3.99	0.00	0.00	0.00	0.00	0.00	0.00	1.64
	-2.5	0.21	8.70	0.00	17.59	0.00	0.00	0.00	0.00	0.00	0.00	7.86
4	-2.0	0.25	5.57	0.00	32.20	0.74	0.99	6.78	0.17	12.30	0.21	15.70
	-1.5	0.36	8.70	0.05	43.08	2.67	2.47	10.81	1.18	25.48	2.03	22.24
2	-1.0	0.82	13.13	0.21	50.69	5.57	4.90	13.69	2.79	38.08	5.18	27.03
	-0.5	2.36	20.71	0.81	57.39	11.07	9.12	18.13	5.97	51.81	11.48	32.03
1	0.0	6.76	32.38	2.50	64.62	20.02	16.56	24.56	12.27	64.69	21.87	38.59
	0.5	22.81	46.55	8.38	71.73	33.23	27.50	34.26	24.40	74.50	36.62	47.34
0.5	1.0	56.04	66.27	17.87	80.68	54.11	46.23	51.51	48.57	83.20	60.08	63.24
	1.5	89.17	84.22	41.82	88.92	76.37	68.11	73.78	76.76	90.18	81.89	82.19
0.25	2.0	98.16	96.58	77.87	95.47	92.77	87.29	91.66	95.11	96.10	95.44	94.07
	2.5	99.76	99.41	95.15	98.21	98.24	95.70	97.62	99.32	98.51	99.22	97.21
pan	3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Alameda 2002

sieve mm size	phi size ♦	al-2002-02	al-2002-04	al-2002-05
8	-3.0			
	-2.5			
4	-2.0			
	-1.5			
2	-1.0	1.91	1.90	3.79
	-0.5	4.96	4.99	7.94
1	0.0	13.34	12.34	15.86
	0.5	27.95	26.73	29.47
0.5	1.0	53.02	54.41	53.02
	1.5	78.48	82.15	75.91
0.25	2.0	93.95	96.34	88.73
	2.5	98.14	99.22	93.13
pan	3.0	99.04	99.81	96.50

South Paseo Del Norte 2002

Phi Size	ps-1	ps-2	ps-3	ps-4	ps-5	ps-6	ps-7	ps-8	ps-9	ps-10
-2.0	2.1	1.2	1.8	0.3	0.25	0.63	9.6	0.54	0.45	3.83
-1.5	2.7	3.5	3	1.38	0.53	1.66	13.39	0.94	0.85	4.96
-1.0	4	6.3	5.58	3.38	1.97	4.04	18.35	1.15	1.62	5.95
-0.5	6.5	11.8	10.67	6.88	5.75	8.13	25.44	2.01	2.79	7.27
0.0	11.8	22.4	19.76	13.72	15.26	15.56	38.34	3.88	8.28	9.99
0.5	22.7	40.9	32.85	27.02	33.42	27.93	50.54	8.87	15.77	18.07
1.0	45.2	66	52.35	50.07	61.27	48.16	67.2	21.68	39.18	41.67
1.5	75.3	87.2	73.4	76.52	84.78	72.15	83.49	48.17	71.25	76.9
2.0	95.9	97.6	91	94.6	96.91	91.32	96.47	80.2	93.72	96.46
2.5	99.6	99.9	97.09	99.25	99.36	97.73	99.51	96.1	98.53	98.54
Pan	100	100	98.89	99.83	99.75	99.99	100.01	98.82	99.59	99.42

2001 Reach Wide Pebble Count and Sieve Analysis 2001

Loc. phi #	n of bern bridge* % Coarser	s. of bern bridge* % Coarser	rio rancho* % Coarser	rio rancho % Coarser	rio rancho % Coarser	corrales* % Coarser	alameda % Coarser	paseo south % Coarser
-8	0	0						
-7.5	1	0						
-7	6	2				0		
-6.5	24	5				0		
-6	61	29	0			8		
-5.5	78	58	10			32		
-5	91	78	25			67		
-4.5	99	93	42			85		
-4	100	98	69			92		
-3.5		100	91			95		
-3.0			100	21.98	35.22	99		
-2.5				24.53	47.48	99		
-2.0				26.36	56.25	100	0.38	2.07
-1.5				28.69	58.89		1.02	3.291
-1.0				31.58	60.29		2.38	5.234
-0.5				34.59	61.24		5.38	8.724
0.0				39.26	62.91		11.78	15.499
0.5				44.8	66.55		23.92	27.807
1.0				51.22	72.9		45.12	49.318
1.5				56.79	77.58		68.66	74.716
2.0				64	82.17		86.66	93.438
2.5				71.51	84.88		94.496	98.561
3				85.03	86.51		99.415	99.58888889
3.5				94.02	87.94			
4				99.89	90.58			
pan					99.61			

* pebble count data.

Alameda 2001

Phi Size	A-1-01	A-2-01	A-3-01	A-4-01	A-1-01b	de average of % Coarser
-2.0	0.80	0.10	0.10	0.20	0.70	0.38
-1.5	2.00	0.20	0.60	0.30	2.00	1.02
-1.0	4.40	0.50	2.00	0.40	4.60	2.38
-0.5	9.00	1.80	5.10	1.40	9.60	5.38
0.0	18.00	6.20	12.20	3.90	18.60	11.78
0.5	33.30	16.30	25.90	9.20	34.90	23.92
1.0	58.50	35.30	50.90	19.20	61.70	45.12
1.5	84.80	58.50	79.00	34.00	87.00	68.66
2.0	97.90	79.50	95.80	62.30	98.00	86.66
2.5	99.70	90.90	99.10	83.20	99.58	94.496
Pan	100.00	99.50	99.80	98.60	99.76	99.532

Bin Analysis from levee priority site south of Bern Bridge
Data has been compiled from pebble count data found in marked sheet in this file

-7	.00%
-6.5	.00%
-6	8.00%
-5.5	32.00%
-5	67.00%
-4.5	85.00%
-4	92.00%
-3.5	95.00%
-3	99.00%
-2.5	99.00%
-2	100.00%

Bin analysis from Rio Rancho north of Barrancas arroyo
this is compiled pebble count data

-8	.00%
-7.5	.00%
-7	2.06%
-6.5	9.28%
-6	29.90%
-5.5	59.79%
-5	80.41%
-4.5	95.88%
-3.5	100.00%

Bin analysis from Rio Rancho north of Barrancas arroyo
this is compiled pebble count data

-6	.00%
-5.5	10.31%
-5	25.77%
-4.5	43.30%
-4	71.13%
-3.5	93.81%
-3	100.00%

phi size f	Bernalillo sand cumulative weight %	Rio Rancho Sand Rivers Edge 2	Rio Rancho Sand repeat	Corrales Sand	Corrales Sand repeat
-3.0	24.99	27.58	22.00	21.38	35.36
-2.5	34.77	29.49	24.56	36.84	47.67
-2.0	39.56	30.75	26.39	46.78	56.47
-1.5	41.85	32.24	28.72	50.15	59.12
-1.0	43.41	34.07	31.61	52.23	60.52
-0.5	45.12	36.47	34.63	53.71	61.48
0.0	47.65	43.08	39.30	56.02	63.16
0.5	53.04	47.77	44.85	60.83	66.81
1.0	62.68	53.24	51.27	67.64	73.19
1.5	74.69	58.25	56.85	73.00	77.88
2.0	84.49	65.13	64.07	77.83	82.49
2.5	92.09	72.52	71.59	80.90	85.21
3.0	100.00	100.00	85.12	100.00	86.85
3.5			94.13		88.28
4.0			100.00		89.50
>4.0					97.34

Sand Samples through the Transition Zone 2002

phi size f	corr-2-02 cumulative weight %	corr-3-02	corr-4-02	corr-5-02	rr-11-02	rr-10-02
-2.5	0	0	0	35.65	0	0
-2	0	0	0	44.72	0	0
-1.5	0	0	0	54.58	0	0
-1	26.33	14.90	26.77	60.16	29.78	9.13
-0.5	34.21	27.15	37.40	64.55	42.06	13.29
0	42.16	41.35	49.82	67.73	56.42	20.16
0.5	49.92	54.68	62.61	70.09	68.13	29.99
1	61.33	69.11	75.97	73.05	79.16	49.39
1.5	77.56	82.69	85.61	75.79	87.66	74.74
2	92.54	93.72	93.37	100.00	94.66	92.57
2.5	97.52	98.41	98.48		98.88	96.16
3	99.17	99.63	99.78		99.89	99.14
3.5	100.00	100.00	100.00		100.00	100.00

Sediment Samples from Barrancas Arroyo South to Alameda. 52 Sample locations total in this section divided into groups of 10 samples each

mm	phi size	ro-1-03	ro-2-03	ro-3-03	ro-4-03	ro-5-03	ro-6-03	ro-7-03	ro-8-03	ro-9-03	ro-10-03
2	-1.0	48.41	1.60	26.92	1.02	13.62	58.53	47.54	3.34	0.58	0.08
	-0.5	53.29	2.49	29.78	6.92	17.84	59.54	52.46	3.95	0.84	0.84
1	0.0	57.10	3.73	32.98	10.71	21.47	63.46	56.96	7.12	1.49	2.49
	0.5	60.45	5.70	36.81	12.98	24.24	66.62	62.73	10.98	2.61	3.91
0.5	1.0	65.29	9.18	44.14	15.21	27.45	69.77	70.53	15.01	5.59	5.17
	1.5	72.43	12.20	56.55	17.87	32.77	72.28	77.55	21.55	16.01	6.18
0.25	2.0	82.34	14.13	75.54	24.49	47.60	74.83	82.77	31.78	45.33	7.43
	2.5	90.92	18.17	87.44	34.73	71.32	77.22	85.76	45.12	75.35	9.65
0.125	3.0	94.67	41.32	91.78	44.91	83.84	80.00	87.58	61.77	88.86	18.49
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-11-03	ro-12-03	ro-13-03	ro-14-03	ro-15-03	ro-16-03	ro-17-03	ro-18-03	ro-19-03	ro-20-02
2	-1.0	0.00	47.98	23.83	51.09	0.00	8.24	28.80	32.91	33.12	1.52
	-0.5	0.09	48.94	26.20	54.32	0.26	9.75	32.02	43.76	40.31	3.25
1	0.0	0.19	50.23	28.40	57.67	1.75	13.47	34.37	52.41	45.93	8.66
	0.5	0.20	51.58	30.36	61.10	3.38	16.44	35.92	59.00	49.99	20.04
0.5	1.0	0.32	53.08	32.52	64.84	4.62	18.51	37.67	65.42	54.09	40.42
	1.5	0.72	54.45	34.76	68.17	5.66	20.00	41.03	73.44	59.19	60.24
0.25	2.0	2.93	56.72	37.54	71.65	6.74	21.54	47.05	81.92	65.27	73.46
	2.5	14.02	60.49	40.64	75.93	7.98	23.11	56.68	87.37	69.37	81.07
0.125	3.0	41.24	66.28	47.29	84.93	10.50	25.61	72.00	94.52	72.72	87.43
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-21-03	ro-22-03	ro-23-03	ro-24-03	ro-25-03	ro-26-03	ro-27-03	ro-28-03	ro-29-03	ro-30-03
2	-1.0	31.63	67.24	47.66	4.59	0.67	0.38	30.76	42.64	31.24	34.22
	-0.5	33.47	70.43	50.79	5.44	0.80	0.43	39.87	43.01	34.89	42.77
1	0.0	37.34	74.20	55.34	8.06	1.51	0.63	50.44	44.63	38.74	50.64
	0.5	43.47	78.30	62.86	10.58	2.57	1.02	62.93	46.37	44.14	59.13
0.5	1.0	53.98	84.19	74.76	12.89	4.03	1.64	76.16	47.87	54.89	69.03
	1.5	65.63	89.34	85.55	15.40	5.26	2.61	91.77	49.27	69.92	79.29
0.25	2.0	73.40	92.75	92.15	18.55	6.61	4.14	96.17	50.65	79.28	87.28
	2.5	78.11	94.68	95.03	23.65	9.33	6.24	96.53	52.39	84.47	90.16
0.125	3.0	81.78	98.01	96.44	33.74	16.18	13.17	96.99	56.13	89.56	92.47
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-31-03	ro-32-03	ro-33-03	ro-34-03	ro-35-03	ro-36-03	ro-37-03	ro-38-03	ro-39-03	ro-40-03
2	-1.0	1.55	17.11	0.77	1.79	10.76	3.76	6.78	3.82	0.20	5.33
	-0.5	4.83	23.01	2.15	4.54	18.66	8.69	13.98	6.37	0.98	10.93
1	0.0	11.79	29.20	6.92	11.41	28.69	18.15	24.36	18.14	3.61	23.04
	0.5	24.43	34.70	17.99	26.43	40.90	33.38	37.53	35.66	11.04	43.59
0.5	1.0	44.08	40.04	38.25	51.38	57.42	53.59	54.79	60.56	26.07	71.45
	1.5	65.11	47.36	60.13	74.97	75.95	72.91	74.33	81.84	53.99	91.77
0.25	2.0	81.26	59.42	72.52	90.47	92.00	88.09	90.81	94.84	76.79	98.89
	2.5	87.36	72.74	76.33	95.54	97.92	94.34	97.89	98.75	87.53	99.75
0.125	3.0	90.41	83.24	83.16	98.62	99.67	98.84	98.61	99.67	95.79	99.84
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-41-03	ro-42-03	ro-43-03	ro-44-03	ro-45-03	ro-46-03	ro-47-03	ro-48-03	ro-49-03	ro-50-03	ro-51-03	ro-52-03
2	-1.0	2.43	0.52	40.27	10.84	23.99	7.64	14.78	3.89	1.21	12.06	1.41	4.47
	-0.5	5.75	1.19	58.73	20.57	30.34	16.59	24.79	9.03	3.61	18.74	3.41	9.00
1	0.0	12.27	4.09	72.76	34.99	39.54	32.80	37.07	19.02	9.76	28.73	8.69	18.54
	0.5	24.11	11.94	82.15	52.64	50.52	55.39	50.86	33.96	23.91	42.19	19.67	35.59
0.5	1.0	45.85	25.23	89.62	72.98	63.51	79.08	65.81	55.17	50.15	60.91	40.29	61.71
	1.5	74.26	38.22	96.02	88.94	75.49	94.81	82.07	75.31	79.85	79.45	63.91	86.96
0.25	2.0	93.94	47.26	99.22	97.00	84.07	99.29	95.56	88.29	96.20	90.90	81.74	98.13
	2.5	98.52	55.39	99.71	99.17	88.45	99.72	99.03	96.62	99.28	94.99	92.93	99.79
0.125	3.0	99.77	69.06	99.81	99.83	93.07	99.79	99.74	99.44	99.79	98.05	97.78	99.94
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-60-03	ro-61-03	ro-62-03	ro-63-03	ro-64-03	ro-65-03	ro-66-03	ro-67-03	ro-68-03	ro-69-03
2	-1.0	1.58	0.70	3.23	0.95	56.22	2.16	6.94	6.53	0.85	2.92
	-0.5	4.50	2.19	8.14	2.97	60.60	4.55	14.69	13.35	2.35	7.09
1	0.0	12.13	6.88	18.13	9.10	64.56	10.00	29.15	24.52	6.34	16.98
	0.5	26.05	16.82	35.24	20.60	68.56	20.66	47.68	38.91	14.89	34.03
0.5	1.0	49.44	36.48	60.24	42.47	73.56	40.81	67.88	56.31	30.54	59.56
	1.5	74.30	64.15	82.25	70.81	79.91	68.40	84.90	74.39	53.09	83.03
0.25	2.0	91.77	87.48	92.90	88.79	86.36	90.97	95.59	88.48	75.57	96.39
	2.5	97.60	95.34	95.11	93.20	89.94	98.24	98.32	95.21	86.44	99.47
0.125	3.0	99.30	97.13	95.93	94.85	93.88	99.53	98.89	98.25	91.55	99.89
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

mm	phi size	ro-70-03	ro-71-03	ro-73-03	ro-74-03	ro-75-03	ro-77-03	ro-78-03	ro-79-03	ro-80-03	ro-81-03
2	-1.0	1.83	5.01	3.23	4.27	1.10	21.32	0.37	3.26	0.81	11.23
	-0.5	4.92	9.66	6.61	11.13	3.46	28.99	1.32	7.03	2.94	17.53
1	0.0	12.45	19.20	13.88	24.36	9.22	37.58	5.39	14.40	9.09	25.74
	0.5	26.40	34.76	25.41	44.01	21.25	46.55	14.91	27.05	20.15	35.77
0.5	1.0	49.66	54.35	42.49	66.66	42.67	58.05	35.86	50.50	37.68	49.02
	1.5	76.53	74.75	63.81	88.45	70.70	71.29	64.89	77.57	55.89	64.14
0.25	2.0	94.45	90.63	87.68	97.89	91.71	84.67	86.97	93.97	70.42	80.07
	2.5	99.21	96.58	97.13	99.69	98.47	93.54	94.30	98.28	80.46	91.90
0.125	3.0	99.90	98.61	99.48	99.90	99.73	97.97	97.80	99.29	89.39	98.09
pan	> 3.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Appendix B   Water surface profile data

PointName	X	Y	corrected level elev (m, arbitrary datum)	level elev (m, arbitrary datum)	point to point distance (m)	cummulative distance m	earth curvature correction for each point	sum of corrections	corrected elevation
h2osurf#1	358524.88	3910103.39	97.90	97.90	0.00	0.00	0	0	97.90
h2osurf#2	358517.75	3910035.14	97.87	97.87	68.62	68.62	0.000317851	0.000317851	97.87
h2osurf#3 tbm2	358497.19	3909927.32	97.77	97.77	109.76	178.38	0.000813231	0.001131082	97.77
h2osurf#4	358455.11	3909888.25	97.69	97.69	57.42	235.81	0.00022256	0.001353642	97.69
h2osurf#5	358372.88	3909803.46	97.49	97.49	118.11	353.92	0.0009417	0.002295342	97.49
h2osurf#6	358304.22	3909707.37	97.25	97.25	118.10	472.02	0.000941455	0.003236798	97.26
h2osurf#7	358311.5	3909467	97.05	97.05	240.48	712.50	0.003903575	0.007140372	97.06
h2osurf#8	358293.02	3909261.29	96.82	96.82	206.54	919.04	0.002879423	0.010019795	96.83
h2osurf#9	358272.16	3909080.51	96.60	96.60	181.98	1101.02	0.002235367	0.012255162	96.61
h2osurf#10	358220.36	3908930.69	96.50	96.50	158.52	1259.54	0.001696226	0.013951388	96.51
h2osurf#11	358287.56	3908777.68	96.33	96.33	167.12	1426.66	0.001885133	0.015836521	96.35
h2osurf#12	358182.33	3908611.63	96.19	96.19	196.59	1623.24	0.002608602	0.018445123	96.21
h2osurf#13	358057.85	3908415.81	96.00	96.00	232.04	1855.28	0.00363425	0.022079373	96.02
h2osurf#14	357851.52	3908200.66	95.73	95.73	298.10	2153.37	0.005998157	0.028077531	95.76
h2osurf#15	357646.91	3908092.78	95.59	95.59	231.31	2384.68	0.003611476	0.031689007	95.62
h2osurf#16	357406.97	3907948.34	95.41	95.41	280.06	2664.74	0.005294303	0.036983309	95.45
h2osurf#17	357151.11	3907829.94	95.24	95.24	281.93	2946.67	0.005365096	0.042348405	95.28
h2osurf#18	356863.68	3907702.49	95.02	95.02	314.42	3261.09	0.006673017	0.049021422	95.07
h2osurf#19	356607.39	3907454.85	94.77	94.77	356.38	3617.47	0.008573184	0.057594606	94.83
h2osurf#20	356382.85	3907241.53	94.52	94.52	309.72	3927.19	0.006474845	0.064069451	94.58
h2osurf#21	356261.24	3907111.13	94.32	94.32	178.31	4105.50	0.002146038	0.066215489	94.39
h2osurf#22	356119.49	3906837.22	94.12	94.12	308.41	4413.91	0.006420583	0.072636072	94.19
h2osurf#23	356049.93	3906593.25	93.92	93.92	253.69	4667.60	0.004344297	0.076980369	94.00
h2osurf#24	355797.67	3906436.65	93.65	93.65	296.92	4964.52	0.00595071	0.082931079	93.74
h2osurf#25	355458.26	3906259.59	93.37	93.37	382.82	5347.34	0.009892084	0.092823163	93.47
h2osurf#26	355161.49	3906093.88	93.08	93.08	339.90	5687.24	0.007798426	0.100621589	93.18
h2osurf#27	354867.81	3905909.05	92.91	92.91	347.00	6034.24	0.00812768	0.108749269	93.01
h2osurf#28	354732.87	3905544.42	92.60	92.60	388.80	6423.04	0.010203559	0.118952828	92.72
h2osurf#29	354704.62	3905490.09	92.47	92.47	61.24	6484.27	0.000253112	0.11920594	92.59
h2osurf#30	354643.57	3905473.63	92.45	92.45	63.23	6547.50	0.000269867	0.119475808	92.57
h2osurf#31	354651.04	3905266.38	92.18	92.18	207.38	6754.89	0.002903065	0.122378872	92.31
h2osurf#32	354759.41	3904989.94	91.95	91.95	296.92	7051.81	0.005951011	0.128329884	92.08
h2osurf#33	354708.72	3904639.29	91.73	91.73	354.29	7406.10	0.008472931	0.136802814	91.87
h2osurf#34	354682	3904245	91.37	91.37	395.33	7801.43	0.010549238	0.147352053	91.52
h2osurf#35	354745	3903844	91.03	91.03	405.83	8207.27	0.011117354	0.158469407	91.19
h2osurf#36	354814	3903859	90.96	90.96	70.61	8209.34	0.000336555	0.158805962	91.12
h2osurf1019-tbm	354766	3903710	90.90	90.90	156.22	8342.48	0.001647286	0.160453248	91.06
h2osurf1019#2	354868	3903472	90.77	90.77	259.38	8596.43	0.004541222	0.164994469	90.93
h2osurf1019#3	354884	3903403	90.63	90.63	70.83	8596.43	0.000338648	0.165333117	90.80
h2osurf1019#4	354884	3903403	90.63	90.63	0.00	8667.26	0.00	0.165333117	90.80
h2osurf1019#5	354879	3903397	90.63	90.63	8.35	8675.79	4.70397E-06	0.165337821	90.79
h2osurf1019#6	354915	3903289	90.32	88.59	113.74	8785.35	0.00087317	0.16621099	90.49
h2osurf1019#7	355020	3902906	90.01	90.01	397.05	9189.04	0.010641449	0.176852439	90.19
h2osurf1019#8	355116	3902656	89.80	89.80	268.10	9454.60	0.004851866	0.181704305	89.98
h2osurf#45	355115.9	3902655.75	89.80	90.40	0.00	9454.60	0.00	0.181704305	89.98
h2osurf#46	355416.87	3901808.44	89.11	89.71	899.18	10353.77	0.054574909	0.236279215	89.35
h2osurf#47	355580.96	3900772.16	87.96	88.56	1049.19	11402.97	0.074304119	0.310583334	88.27
h2osurf#48	355641.9	3900393.5	87.53	88.13	383.53	11786.50	0.009929053	0.320512387	87.85
h2osurf#49	355145.66	3899649.2	86.36	86.96	894.56	12681.06	0.054015972	0.374528359	86.74
h2osurf#50	354488.33	3899131.61	85.35	85.95	836.65	13517.71	0.047248794	0.421777154	85.77
h2osurf#51	354026	3898443.87	84.91	85.51	828.69	14346.40	0.046354635	0.468131789	85.38
h2osurf#52	353429.75	3897907.62	84.27	84.87	801.92	15148.32	0.043407773	0.511539562	84.78
h2osurf#53	352833.69	3897540.96	83.70	84.30	699.81	15848.13	0.033056578	0.54459614	84.25
h2osurf#54	352279.29	3897268.73	83.16	83.76	617.63	16465.76	0.025749126	0.570345266	83.73
h2osurf#55	352280	3897268.52	83.16	83.76	0.74	16466.50	3.70035E-08	0.570345303	83.73

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